Metra Electric District

MOTIVE POWER STUDY

Evaluation of Traction Power System

Evaluation of Existing System

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Volume 2: Evaluation of Existing System

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1. INTRODUCTION

1.1 HISTORICAL PERSPECTIVE

1.1.1 Railroad Beginning

The rail lines now operated by the Metra Electric District were originally built by the Illinois Central Railroad (IC). The IC had begun operating southward from Hyde Park (53rd Street) on May 22, 1852. The first IC suburban service trains began running on July 21, 1856 from Randolph Street terminal to Hyde Park. The ridership grew at a spectacular rate, doubling between 1900 and 1920, by which time there were 294 daily train runs. To cope with the high number of passengers, the IC developed a highly efficient operation, introduced high level station platforms, purchased the Sullivan type cars with 10 doors per side, and began considering electrification.

1.1.2 Choice of Electrification System

Various systems of electrification were carefully studied before a choice was made. The choice was between direct current (DC) systems at moderate electrification voltage and alternating current (AC) systems at high electrification voltage. The DC systems would require more elaborate equipment on the wayside, but very simple equipment on the trains. The AC systems, on the other hand, required heavier and more expensive equipment on the trains, but minimal equipment along the wayside.

AC electrification system thus would be a good choice for a long distance electrification involving hundreds of miles of line and relatively few locomotive-hauled or multiple unit (MU) trains. DC system, on the other hand, seemed to be the best choice for the IC system electrification, which would involve only a relatively short line, but hundreds of electric MU cars. Since the traffic on IC's Mainline beyond the suburban territory was too light to offer any economic justification for long distance type of electrification, the choice thus was made to use a 1,500 V DC system. This voltage, about double that used by the elevated system and the streetcars, greatly reduced line losses and allowed substations to be spaced along the route at wider intervals.

1.1.3 Beginning of Electric Service

On July 21, 1926, the first electric suburban train ran from Randolph Street to 67th Street. Formal inauguration of electric operation through to Matteson took place on August 27, 1926. Soon electric trains covered all suburban service on the Mainline to Matteson, and the South Chicago and Blue

Island Branches. By 1929, 542 daily electric suburban trains were handling 121,000 daily passengers and the IC electrification was a resounding success.

1.1.4 Equipment Innovations

While the electrification was initially applied only to the suburban service, it was intended that it would eventually take over all freight and long-distance passenger operation within the city to eliminate smoke and noise of steam operation. The electrification system equipment was selected and designed with great care. For example, the IC requested the two major manufacturers of electrical equipment, General Electric and Westinghouse, to offer traction motors which were completely interchangeable. After extensive testing both motors were found to be satisfactory, and half of the order was placed with each supplier. The control equipment for all cars was supplied by General Electric.

Most of the substations had motor-generator sets to convert the AC power from the utility to the DC power required by the trains. A few of the substations were equipped with mercury arc rectifiers which were just beginning to be available. With no moving parts, the rectifiers required much less supervision and maintenance. A major innovation was that the substations would be owned and operated by Commonwealth Edison, rather than by the railroad. The utility was more accustomed to substation operation than the railroad and realized savings in equipment maintenance through economies of scale.

1.1.5 Recent Equipment Enhancements

In the 1970's the value of commuter service to the community was recognized and the South Suburban Mass Transit District, a predecessor of Metra, was created and provided assistance to the IC, by then merged into the Illinois Central Gulf (ICG) railroad.

New cars were purchased to replace the original electric cars. Following the lead of most of the other railroads operating suburban service in Chicago, the new cars were of the bi-level gallery type, providing the maximum number of seats per car. Because the IC operation, especially at the congested loop stations and the terminal, required passengers to be able to board and alight very quickly, the cars were designed with more doors than those of other railroads.

At the same time, automated fare collection was introduced on the ICG Suburban service as a major innovation. This was the first large-scale application of a system using magnetically-encoded tickets and fare gates which read the tickets electronically. Also, the original rotary converters and mercury-arc rectifiers in the traction power substations were replaced with solid-state rectifiers.

1.1.6 Metra Electric District System Today

In 1982 the operation of the Electric District has been taken over by Metra. Since the suburban passenger operation has been separated from the long-distance passenger and freight operations, the transition has been easier than in cases where commuter and freight operations had to be integrated on jointly-owned tracks.

Immediately upon beginning operation, Metra embarked on a modernization program of its facilities. This modernization included rehabilitation of the existing equipment as well as installation of new facilities.

The Metra Electric District rolling stock consists of 165 Highliner cars built between 1971 and 1978. All cars were overhauled between 1989-1996. The cars have been re-cambered, corroded steel has been replaced, and the car systems were reconditioned with some upgrades. However, the cars will soon reach the end of their useful life.

In the traction power substations, PCB-filled traction power transformers were replaced with dry-type or oil-filled transformers and the original AC and DC circuit breakers were replaced with modern switchgear. The DC feeder cables, the 4.16 kV lighting and power cables, and the 2.3 kV signal power supply cables were also replaced. Additional systems were introduced, such as the supervisory control and data acquisition system (SCADA), the DC circuit breaker fail protection, and the transfer trip protection.

The catenary system has undergone major rehabilitation. Contact wire wear is continuously monitored and significant sections of contact wire have been replaced. Although old, the present system is in a remarkably sound condition. The tensions in the conductors are being monitored and retensioning is performed as required. De-wirements are rare and a program of pole foundation repair is ongoing.

Much of the signal system today needs to be updated. The existing Mainline track circuits with US&S Model 15 relays are still very reliable but their maintenance and repair are costly, as the relays have not been available since the 1970's. The major interlockings, Randolph and Kensington, are in satisfactory condition being equipped with phase-selective coded track circuits. In the near future, the 67th Street Interlocking Tower is going to be replaced and split into three interlockings (65th, 67th and 69th) with the same type of track circuits. The Mainline south of Kensington is in the Centralized Traffic Control (CTC) territory and is controlled from the Central Control Facility (CCF).

The South Chicago Subdistrict signal system has had little or no updates since the 1950's. Along with maintenance of the many AC track circuits, maintenance of insulated joints is required. Because of the 36 (soon to be 38) at-grade crossings, much of the crossing protection has hold down circuits, station dwell time, speed measuring, and interlocking type relays for stick circuits.

The Blue Island Subdistrict is in marginally better condition than South Chicago Subdistrict. The single track systems includes one spring switch passing track.

The communication system for the Electric District is owned and operated by Metra. The system consists of telephone, radio, SCADA, station public address (PA), and station closed circuit televison (CCTV) subsystems. There are two control centers serving the system. The CCF is the principal communications control center for the entire railroad operated by Metra. The second facility is the Passenger Assistance Link (PAL) Center. PAL's main function is to provide a manned communications link, both audio and visual, to Metra passenger stations on the Electric District. The communication equipment located at passenger stations, power substations, and other rail right-of-

way (ROW) locations are connected to the two control centers by fiberoptic, coaxial, and copper cables. These communications connections are supplemented by telephone voice and data circuits leased from Ameritech.

The Metra Electric District has six maintenance and storage facilities, Randolph Street/North Terminal, Weldon/18th Street Yard, Kensington Yard (KYD), Blue Island Yard, Matteson/Richton Park Yard, and University Park Yard/South Terminal. The facilities serve for routine inspection, light repair, major repair and overhaul, exterior car wash, interior car cleaning, wheel truing, and car storage.

The Light and Power (L&P) Transmission System supplies AC electrical power to passenger stations, Maintenance-of-Way (MOW) buildings, street/subway lighting, interlocking towers, bridges, signal system equipment, snow-melter systems, and other locations along Metra Electric District routes. The system consists of two distinct transmission subsystems, L&P Power four-wire, three-phase distribution system rated at 4.16 kV/60 Hertz, and Signal Power two-wire, ungrounded, single-phase distribution system rated at 2.3 kV/60 Hertz. Each of the subsystems receives power from the traction power substations via wire atop the overhead catenary system supports. Duplicate power lines are installed on the most critical portions of the Mainline.

1.2 PURPOSE OF THE STUDY

Since inception of the original electrification system, the electrical equipment operated safely and reliably. Today, some of the original equipment is still in service after more than 70 years of continuous operation. Due to the equipment age, some of the subsystems and components may be at the end of their useful life and need to be upgraded or replaced.

Furthermore, the existing cars that replaced the original electric cars are 20-30 years old. The cars have already undergone one rebuilt cycle, and now the car bodies are deteriorating. The cars still use the obsolete and inefficient cam-controlled propulsion system. With significant investments for the system modernization already committed, and a new large investment to replace the 165 cars potentially ahead, Metra wishes to evaluate the next step in the electric system development and assess how to continue serving the commuter passengers in the new century.

Taking into account the recent and projected passenger volume increases, the primary purpose of this study is to determine the answers to the following fundamental questions:

- What are the rolling stock replacements options? Should the existing rolling stock be replaced with the same type of equipment or should new technology, such as AC propulsion, be introduced?
- Would it be advantageous to use locomotive-hauled trains with trailer cars?
- Should the existing 1,500 V DC traction power supply and distribution systems be retained and augmented with additional power supply facilities to supply the projected level of service, or should the system be converted to a new electrification system operating either at 12.5 kV AC or 25 kV AC electrification voltage?

If the existing system is retained, it is necessary to answer the following:

- What modifications to the existing traction power system are required to supply year 2020 traction loads?
- What new equipment is required and what are the equipment ratings?
- What is the realistic, least service disrupting, and most cost-effective approach for implementing the system augmentation?
- What additional system components need to be renovated and upgraded?
- What is the cost of the system augmentation and upgrade?

In the event that either the 12.5 kV AC or the 25 kV AC system is more advantageous to Metra, the following questions need to be answered:

- What should the configuration of the new system be?
- What impact would the voltage increase and use of commercial frequency have on vehicle modifications, overhead catenary system clearances, signaling system compatibility, and change of other miscellaneous subsystems?
- What would be the environmental impact of the system conversion?
- What would be the operational impacts of voltage and frequency changes on Metra and the Northern Indiana Commuter District (NICTD)?
- What is the realistic, least time-consuming, and most cost-effective approach for implementing the system conversion?
- How would the system conversion be accomplished with minimum disturbance to train operation during construction?
- How would the new system construction be coordinated with vehicle conversion?
- What other system improvements are necessary due to obsolete equipment and change in voltage and frequency?
- What are the impacts of construction of new transmission lines for power supply to new substations?
- What are the major risks to successful project implementation?
- What is the cost of the system conversion?

Additionally, an evaluation into the possibility of dual-power locomotive (DPL) use is required. In the event that Metra extends its service in the future, *e. g.*, to the proposed South Suburban Airport (SSA) planed to be located near Peotone, Ill, by the State of Illinois Department of Transportation (IDOT), the DPL-hauled trains would be an option to extension of the electrification system.

1.3 SCOPE OF WORK

The Metra Electric District consists of the Mainline rail route between the downtown Chicago Randolph Street Station and the University Park Terminal. There are also two spur rail lines branching off of this Mainline, the South Chicago Branch and the Blue Island Branch. The study evaluates the systems used on the Metra Electric District commuter lines as shown in Table 1-1.

Table 1-1 - Metra Electric District Commuter Lines

Line Name	Extent of the Study	Approximate Route Length (miles)	Number of Passenger Stations	Maximum Operating Speed (mph)
System Mainline	Randolph Street to University Park	31.4	34	65
South Chicago Branch	Mainline to South Chicago 93rd Street	4.7	8	30
Blue Island Branch	Mainline to Blue Island	4.4	7	30
Total System Under Study		**40.5**	**49**	

1.4 METHODOLOGY

The work on the project is divided into three tasks, and each task is, in turn, divided into subtasks as shown in Table 1-2.

Table 1-2 - Metra Electric District Study Tasks and Subtasks

Metra Study Tasks	Study Subtasks
Task 1: Data Collection, Site Inspection, Interviews, and Inventory of Existing System	1.1 Data Collection and Review 1.2 System Inspection and Evaluation 1.3 Staff Interviews 1.4 Inventory of Existing System
Task 2: Evaluation of Existing System	2.1 Existing Operation Criteria 2.2 Rolling Stock 2.3 Traction Power System 2.4 Catenary System 2.5 Signal System 2.6 Communications System 2.7 Storage and Maintenance Facilities 2.8 Light and Power Transmission Line 2.9 Real Estate Requirements 2.10 Environmental Impact 2.11 Cost Estimates 2.12 Recommendation and Implementation
Task 3: Project Definition/Concept Planning	3.1 Design Criteria 3.2 Rolling Stock 3.3 Traction Power System 3.4 Catenary System 3.5 Signal System 3.6 Communications System 3.7 Storage and Maintenance Facilities 3.8 Light and Power Transmission Line 3.9 Real Estate Requirements 3.10 Environmental Impact 3.11 Cost Estimates 3.12 Conclusions and Recommendations

The work performed in Task 1 is an indispensable effort which forms the cornerstone of the Motive Power Study. The purpose of the task is to prepare an overview and inventory of the Metra Electric District system elements, vehicles, and facilities.

Based on the Task 1, analysis of the existing Metra systems, vehicles, and facilities is performed in the Task 2 with regard to future system operation costs. A comprehensive power system study is performed for the current passenger density, and systems and facilities needing augmentation are identified. As some of the system components are more than 70 years old and might be close to the end of their useful life, consideration is given to future maintenance costs. The objective of this task is to evaluate and determine which parts of the Metra Electric District system can continue to be used, which parts need upgrading, and which parts need replacement.

In Task 3, alternative systems that could either supplement or replace the existing 1,500 V DC electrification system are evaluated taking into consideration passenger density projected for the year 2020. Any proposed electrification system needs to have sufficient capacity to supply adequate power to the trains and meet future system operating requirements. The objective of this task is to develop conceptual designs for at least three alternative systems, each capable of supporting Metra's operation projected to the year 2020. Impacts, benefits and costs of each system are required to be developed, and the most advantageous system for the Metra Electric District needs to be identified.

1.5 WORK PRESENTATION

Consistently with the three tasks outlined above, the Metra Motive Study report is presented in the following volumes:

- Volume 1 - Data Collection, Site Inspection, Interviews, and Inventory of Existing System
- Volume 2 - Evaluation of Existing System
- Volume 3 - Project Definition and Concept Planning

In order for each volume to be a stand-alone document, this introductory Section 1.0 is presented in each volume. For a comprehensive project overview, however, the reader should have an access to all three volumes.

2. EXISTING OPERATION CRITERIA

The existing system operation data were determined from published timetables[1] and discussions with Metra staff. The key data collected for peak time periods of operation included:

- Train departure times.
- Passenger station stopping pattern and dwell time. The passenger station dwell time of all trains was assumed to be 30 seconds.
- Train consist sizes.

The data were collected for the following routes[2]:

- System Mainline, Randolph Street to University Park
- South Chicago Branch, Randolph Street to South Chicago 93rd Street
- Blue Island Branch, Randolph Street to Blue Island

The operational data were used in the computer-aided traction power system load-flow study simulations presented in Chapter 4 of this report.

1 Metra Timetable, Chicago to University Park, Effective May 2, 1999 and NICTD Timetable, Effective May 1, 2000.

2 V.L. Stoner Chief Operations Officer and G.L. Hardwidge Chief Transportation Officer, Metra Operations Profile.

3. ROLLING STOCK

3.1 PERFORMANCE CHARACTERISTICS

The vehicle physical dimensions, tractive effort vs. speed curve as well as acceleration and braking rates were collected and used in the vehicle performance calculations and traction power system simulations. Two vehicle types operate over the study area, Metra Highliner gallery cars and NICTD single level cars. Because the Metra cars are heavier, they have been used as a conservative basis for all traction power system analysis.

Both car types originally used identical General Electric resistance cam control and GE 1258 traction motors. Metra has modified the GE equipment due to service experience. Metra modifications include elimination of traction motor field shunting and replacement of high current pneumatic GE contactors with EMD magnetic contactors. These two modifications are reviewed below and their effect on vehicle performance is evaluated.

3.1.1 Motor Field Shunting Elimination

The present Metra GE equipment has been operating with field shunting disabled to improve traction motor reliability and decrease energy consumption. Field shunting is a motor control method that enables the traction motors to operate at essentially constant power above the base speed[3] by weakening current in the DC motor field. The field shunting significantly improves the rolling stock acceleration at high speeds and top speed capability. The impact of re-introduction of the traction motor field shunts on the vehicle performance and the traction power substation demands was investigated and the results are presented in Chapter 4.

The disadvantage of the field shunting is that the peak current of rolling stock, associated with constant peak power, is drawn for a longer period of acceleration time. The net effect is that the total rolling stock acceleration time to reach a given speed, or to traverse a given distance, is reduced, but the substation power demand is increased. However, since the individual cars of the train shunt the field at slightly different times, the net rate of the line current surge of the whole train is not as large as it would be for simultaneous shunting of all cars. Therefore, the rate of line current rise alone does not adversely impact the equipment in traction power substations such as circuit breakers, traction power transformers, and rectifiers.

[3] The base speed attained by the rolling stock when all control resistance is out of the motor armature circuit.

Normally, when rolling stock is equipped with a cam controller, field shunting is performed in several steps. This result in the line current, motor current, and the tractive effort variation in a saw-tooth fashion. The saw-tooth approximates constant power operation. For the Metra cars, the original GE cam control equipment provided only one step of field shunting, from 100% to 50% field strength. This single large step resulted in motor current surge and was blamed for poor motor reliability.

The reduction of the traction motor commutator problem when field-weakening is eliminated was evaluated separately by both Metra and NICTD. Using essentially identical GE propulsion equipment, Metra eliminated the field weakening while NICTD retained the field weakening. Removal of field weakening avoids an increase in flashovers when operating in weak field, but as already discussed, the performance of the cars is adversely affected.

In the event that the Metra fleet is replaced with rolling stock equipped with inverter drives, the traction motor related disadvantages will be of no further concern. The performance of the new propulsion equipment need to be included in any traction power network analysis. A credible upper-bound for performance and current draw data is represented by the Toshiba inverter drive equipment now being procured by NICTD.

The Toshiba inverter equipment is also capable of regenerative braking which will reduce hotel load energy consumption on individual cars and can reduce the overall traction power demand in dense traffic areas such as the throat to Randolph Street Station and along the trunk line to Kensington. This is achieved through train-to-train power transfer via the shared overhead catenary system.

3.1.2 Pneumatic Contactor Replacement

The pneumatic contactors originally used in the Metra General Electric resistance cam control equipment serve as current switches in the 1,500 V DC motor circuits. These specialized GE devices required unique maintenance attention and involved expensive replacement parts. Similar current switching is involved in diesel locomotive controls, but at lower voltages. Metra modifications include replacement of high current pneumatic GE contactors with EMD locomotive magnetic contactors. The change did not alter the function of the GE propulsion equipment and hence does not have any impact on the power study.

3.2 ROLLING STOCK EVALUATION

3.2.1 Present Rolling Stock Condition

Following the visit to the Metra KYD shop and examination of several in-service Highliner cars, the report prepared by Virginkar/STV[4] was reviewed, and additional discussions were held with Metra

[4] **The Economic Life Analysis Study Report for Metra Highliner Cars**, Virginkar & Associates in association with STV, April 1999.

staff. The report and the follow-up discussions revealed that many of the Highliner cars had far more extensive corrosion than was evident in the Highliner cars examined. Additionally, this investigation made clear that rebuilding or rehabilitation of the present fleet is not practical because some cars have structural weakness that cannot be permanently corrected.

Based on these evaluations, it was concluded that the entire fleet of rolling stock should be replaced. The replacement rolling stock would be of modern design, with up-to-date systems and materials, including AC propulsion and stainless-steel body. The following Highliner car replacement options were identified:

- Replacement of the Highliner cars in kind.
- Provision of single level MU high performance cars.
- Provision of push-pull Highliner type cars.

These options are discussed in the following sections.

3.2.2 Replacement of Highliner Cars in Kind

In kind replacement of Highliner cars would represent replacement of the existing cars with substantially the same bi-level electric multiple units (MUs). Since all rolling stock subsystems would be of modern design, the new cars would have higher performance and lower maintenance costs than the present Highliner cars.

The higher performance of new cars may make variation on the "all MU" fleet possible, while still maintaining the present passenger throughput. One of every three cars could be a non-propulsion car. This would reduce fleet acquisition and maintenance costs due to a lower capital cost and no MU inspections requirement for the trailer cars. The end powered cars would be provided with cabs and the middle trailer car could be redesigned for higher passenger capacity.

3.2.3 Provision of Single Level MU High Performance Cars

Replacement of the Metra bi-level Highliner cars with single level MU cars should be investigated. Although the single level MUs have lower seat capacity than the Highliners, they have faster passenger boarding and alighting, and can reduce passenger station dwell time. By combining the higher performance of AC propulsion and the shorter station dwell times, the single level MU cars can run on a tighter schedule. This would allow for more trains to operate during the rush hour and enable the passenger seat capacity of the single level MUs to approach the capacity of the present Highliner cars.

Investigation into single level MU performance will be conducted to determine whether the improved performance of the new cars could lead to schedule improvement that would achieve the required service. Since single level MU cars operating on the same schedule as the Highliner cars cannot equal the Highliner seat capacity, this option will not be studied. However, it is possible that single level cars designed as three car sets with only two doors per car and articulation connections could approach the Highliner seat capacity.

3.2.4 Provision of Locomotive-Hauled Push-Pull Cars

Push-pull cars of the Highliner type are an attractive option because they do not require MU car inspections and their initial cost is lower than the cost of comparable MU cars. Locomotives propel the push-pull cars at one end of the train, while the other end of the train is equipped with a cab car.

The options for push-pull service include the following locomotive types:

- Electric
- Dual-power, combining diesel power and electric power propulsion

The electric locomotives appear the most advantageous for Metra, as the existing system is already electrified. The dual power locomotives combine diesel power and electric power propulsion in a single unit and would appear to be most suitable for partially electrified territories, or for electrified territories where the railroad extensions would not be electrified. The dual-power locomotive diesel engine can be turned off in electrified territory and re-started in non-electrified territory.

In comparing the electric locomotives with the dual-power locomotives, the following factors were considered:

- Horsepower Rating
- Maintenance Cost
- Availability and Reliability
- Purchase Cost and Economic Life
- Performance

3.2.4.1 Horsepower Rating

Electric locomotives can be built with a continuous horsepower rating of 10,000 HP. Modern developments make it possible to achieve ratings even higher than this value. The locomotives have good overload capability, typically 1.7 times the continuous rating for 5 minutes and 1.1 times for one hour.

Diesel engines can be built with ratings of up to 4,400 HP with room for Head End Power (HEP). HEP includes another engine with 800+ horsepower rating. Locomotive ratings up to 6,000 HP can be obtained, but the engines are so long that there is no room for HEP. Diesel engines have negligible overload capability.

3.2.4.2 Maintenance Cost

Industry estimates indicate that the maintenance cost of an electric locomotive is approximately 60 to 65 percent of that for a diesel locomotive[5]. The traction motors and certain control and

[5] M. Ephraim, H.E. Quinn, **Electrification and New Electric Locomotive Design**, Rails Northeast, October, 1977.

mechanical equipment are similar for both electric and diesel locomotives, and thus require the same maintenance. The electric locomotives require periodic inspection and replacement of the pantograph contact strip and some minimal maintenance associated with other electrical equipment, such as the on-board circuit breaker, propulsion transformer, and controlled rectifier unit. The diesel locomotive engine maintenance far exceeds maintenance of the pantograph and electrical equipment of the electric locomotive.

3.2.4.3 Availability and Reliability

Due to the fact that electric locomotives are simpler and with fewer moving parts, the time required for maintenance is less than that for diesel locomotives. Further, as the electric locomotives do not require refueling and therefore their availability for service is higher, being approximately 90 percent, while the availability of the diesel locomotive is approximately only 80 percent.

Once in revenue service, the probability of failure of the electrical equipment in both types of locomotives is relatively low. The failures associated with the diesel engines make the diesel locomotives less reliable than the electrics.

3.2.4.4 Purchase Cost and Economic Life

In considering the purchase cost and economical life of electric and diesel locomotives, the electric locomotive cost is approximately 15 percent lower per horsepower and they have twice the operational life of a diesel locomotive[6].

3.2.4.5 Performance

The central question is whether locomotive-hauled push-pull trains have sufficient acceleration and whether they are fast enough to meet the present Highliner service. The push-pull car performance will be analyzed to determine the likelihood of achieving the present service schedule. In the event that the present schedule cannot be met, investigation will be carried into the possibility of achieving the same level of service by running more trains at a closer headway. In this case, the number of locomotives and push-pull cars required will increase.

The dual-power locomotive, while operating in the diesel mode, would suffer from the disadvantages already discussed. In addition, recently, locomotive manufacturers have been reluctant to bid on dual power locomotives.

3.2.5 Evaluation of Rolling Stock Options

The following advantages and disadvantages of the rolling stock replacement options discussed above were identified:

[6] Edison Electric Institute, **Railroad Electrification, Volume 1**, EEI Publication No. 70-31A5M-6/70.

- **New Highliner Cars**
  - Advantages
    - Lowest cost per passenger seat.
    - Higher performance in comparison with the existing cars.
    - Lower maintenance in comparison with the existing cars.
  - Disadvantages
    - Slower passenger boarding in comparison with single level cars.
    - Highest cost per vehicle.
- **New Single Level MU High Performance Cars**
  - Advantages
    - Moderate cost per car.
    - Faster passenger boarding and alighting.
    - Higher performance in comparison with the existing cars.
    - Lower maintenance in comparison with the existing cars.
  - Disadvantages
    - More cars are needed for equal number of passenger seats in comparison with the existing cars.
    - Possible difficulty in acceptance by passengers and crew.
- **New Push-Pull Highliner Type Cars**
  - Advantages
    - Lowest cost per car.
    - Lower maintenance in comparison with the existing cars, except for wheels and brakes.
  - Disadvantages
    - Locomotive required.
    - Poor performance during acceleration and braking. May require schedule adjustment. Not recommended for station stops less then 1.5 miles apart.
    - Excessive wheel wear, cracked wheels, and frequent brake shoe replacement likely.
    - Limited flexibility with respect to train make-up in comparison with the existing cars.

The new Highliner cars, the single level MUs, and the push-pull cars can be manufactured of stainless steel resulting in the absence of corrosion and up to 20 years projected life before a major rebuilt is required.

A comprehensive study of the identified options for replacement of the present Highliner cars will be performed in Task 3 using the present level of performance of the Highliner cars as a benchmark. For each option, the seat capacity of cars, the equivalent fleet size, and the ability to meet the present revenue service schedule will be taken into account. Further, the capital cost of fleet acquisition will be estimated and the maintenance cost will be developed. Cost of electrical power and energy, as well as cost of fuel, will be considered in developing the overall base costs. Following development of the base costs, future costs of operation and maintenance will be assessed for the various options. A Present Value Analysis will be used to determine the most advantageous option for Metra.

4. TRACTION POWER SYSTEM

4.1 TRACTION POWER LOAD-FLOW STUDY

4.1.1 Purpose of the Study

The purpose of the traction power system load-flow simulation study was to confirm that the traction power system facilities are adequate to support the current train operation. This included the following verifications:

- Locations of the existing traction power substations and tie stations.
- Rating of the existing substations.
- Size of the overhead catenary system.

The basis of the load-flow study is a comprehensive computer-aided simulation of the train operation. The simulation included the following components of the traction electrification system:

- Traction power supply substations.
- Overhead catenary distribution systems.
- Rail return system.

The simulation was based on the existing train operation and configuration of the traction electrification system.

4.1.2 Simulation Software

The basis of the traction electrification system study was a computer-aided load flow analysis of the traction power supply, distribution, and return systems. The study was performed using Energy Management Model (EMM). The EMM is a computer program specifically developed to enable comprehensive modeling and studies of high-speed rail, commuter railroad, and rail transit electrification networks. The program takes into account route alignment data (track gradients, curves, speed restrictions, and passenger station locations), train data (weight, propulsion system characteristic, and braking system parameters), electrical system data (power supply substations and tie stations, overhead distribution system, and negative return systems), and operation data (train consist sizes and timetable schedule).

The program simulates the dynamic train operation in accordance with a given timetable and provides output results which include train voltages, currents at selected locations along the power distribution system, as well as substation power demands and energy consumption.

The EMM consists of two major simulators:

- Train Performance Simulator (TPS)
- Electric Network Simulator (ENS)

4.1.3 Train Performance Simulator

TPS is run first to simulate the operation of trains along the route. The train input data include propulsion system characteristics (tractive effort versus speed data, efficiency, and acceleration rate limit), braking effort data, car weight, train resistance to motion, number of cars in a train consist, auxiliary electric load, and passenger loading. The route alignment input data include the track grades, curves, speed restrictions, passenger station locations, and station dwell times.

The TPS output is tailored to the specific needs and requirements of the simulation. The numerical and graphical outputs were selected from a menu of 39 parameters which include the train speed, acceleration, milepost location, mechanical and electrical power demand, and losses calculated at fixed intervals of time, so-called snapshots. The key TPS output is the train power profile file. The file relates the train power demand calculated at each snapshot to the train location along the system. The file needs to be available for each type of train and for each direction of operation.

4.1.4 Electric Network Simulator

ENS runs are performed following the TPS runs. ENS simulates the electrical network operation while the trains operate along the system according to the given timetable. The ENS input data include parameters describing the electrical traction power supply network as well as the power distribution and negative return systems. Equipment that can be represented by the program include the equivalent utility power system, the substation transformer/rectifier units, tie stations, distribution system, return rails, and various feeders as necessary. The ENS program also accepts the TPS-generated train power profiles, so that the system conditions can be simulated under the dynamics of train movements.

The ENS program calculates train voltages, currents, and power demands at each snapshot and summarizes the calculated values at each traction power substation and at other selected locations along the system. The train voltages predict the overall system performance of the traction system and indicate whether the substations, and tie stations are correctly located. The system currents are used to develop circuit breaker and switchgear ratings, and determine the suitability of the traction power distribution system conductors. The power demands and energy flows through substation metering points provide information required to define ratings of substation transformers and to estimate electric power utility charges.

4.1.5 Study Criteria

4.1.5.1 System Voltages

The suitability of the traction power substation locations were verified taking into account the allowable voltage drop along the system. In a traction power system comprising the utility network,

substation equipment, feeders, catenary conductors, and rails, every train on the system should have available adequate voltage at the pantograph for propulsion purposes. This means that the train voltages should not be allowed to decrease below the values recommended by AREMA as shown in Appendix B.

4.1.5.2 System Currents

The highest currents in the distribution system occur in feeders and catenary system adjacent to the substations. To obtain the highest current values, load currents were calculated at the connections of substation feeders to the catenary system. The calculated load currents were compared with the estimated ampacity of the distribution system, shown in Appendix B, to evaluate the suitability of the catenary conductors.

4.1.5.3 System Power Demands

Substation power demand is of a highly fluctuating nature. This is a result of abrupt, impulse-like changes in power requirements of trains as they accelerate, decelerate, or as they encounter or leave track grades. The magnitude and frequency of the impulses increase during peak time (rush hour) periods as longer trains at shorter headways may be used. The peak power demand time occurs twice a day and typically lasts for 2-4 hours. For traction power substations to supply this load cycle, the substation equipment must have sufficient continuous and overload power ratings.

To confirm the required ratings for the substation traction power transformers, maximum average power demands for each substation were calculated for 2-hour, 15-minute, 5-minute, 1-minute, and 15- second time durations.

4.2 APPLICATION OF THE EMM PROGRAM

4.2.1 Study Procedure

The computer load flow simulations are performed in the following steps:

- Collection of route alignment data, passenger station data, and train data.
- Conversion of collected data into TPS computer input data.
- TPS computer runs.
- Analysis of TPS results.
- Collection of electrical network parameters and system operations data.
- Conversion of collected data into ENS computer input data.
- ENS computer runs.
- Analysis of ENS results.
- Existing system verification and conceptual system design.

The TPS calculations are performed at frequent snapshots, *e.g.*, 1 to 5 second time intervals, and the ENS calculations are performed at snapshots of 5 to 10 second time intervals. Both calculations

therefore generate a considerable amount of results. To simplify review and evaluation of the results, the computer output data are presented in the form of charts and tables.

The program simulates the network conditions under the dynamic conditions of train movement as the trains operate along the system route according to a given timetable. The computer results provide output of the system currents, voltages, as well as power flows and losses. The output data were used for verification of existing substation and tie station locations, verification of the traction power equipment ratings (transformers, rectifiers, and circuit breakers), and confirmation of overhead catenary conductor sizes.

Specifically, the EMM has the capability to identify areas of low voltage and high currents, if present, indicating that substation locations that might not be appropriate for the given system traffic density. Also, the substation power demands can be calculated over several time periods, indicating any possible short-time, long-time, or continuous power overloads.

4.2.2 Study Methodology

The traction power substations are required to be located along the system route at predetermined intervals to ensure that the following conditions are satisfied even under the most severe train operating scenarios:

- The train voltages do not drop below a minimum value that would cause an undue degradation of the train performance.
- The traction power supply equipment is not overloaded causing excessive temperature rise and premature equipment failure.
- The maximum temperature of the distribution system conductors does not exceed the permissible value to prevent copper annealing.

For a given alignment and train operation pattern, the substation spacing and the resulting train voltages, substation power demand, and the catenary current magnitude depend on the train propulsion characteristics, consist sizes, headways, and the proposed system electrical parameters.

4.3 TRAIN PERFORMANCE SIMULATIONS

4.3.1 Runs Performed

The TPS runs were performed for both outbound and inbound runs of each train type. The train type is given by the train consist size and stopping pattern. Most of the Metra trains consist of two, four, and six cars while the NICTD trains consist of four, six, and eight cars. The Metra trains were simulated operating along the following routes:

- Mainline, Randolph Street to University Park
  - Express Trains, Harvey Zone
  - Express Trains, Flossmoor Zone

- Express Trains, University Park Zone
- South Chicago Branch, Randolph Street to South Chicago
- Blue Island Branch, Randolph Street to Blue Island

The NICTD trains were simulated operating between Randolph Street and Kensington.

The TPS runs were performed for the following rolling stock operation:

- Field weakening disabled and maximum train speed limit of 65 mph.
- Field weakening enabled and maximum train speed limit of 65 mph.
- Field weakening enabled and maximum train speed limit of 75 mph.

4.3.2 Input Data

The route profile, operating speeds, and passenger station locations were obtained from Metra[7]. This information was used as an input to the train performance simulation model. The passenger station stopping pattern was obtained from the current timetable and the train consist sizes were obtained from Metra's Capacity Utilization of Trains for Commuter Rail System.

Input data are presented in Appendix C.

4.3.3 Study Results

Summary of the TPS results are presented in Tables 4-1 through 4-3. The results are presented for the three zones of express train operation and are intended to compare the differences in trip time, average speed, and energy consumption for the existing operation and future possible operation options.

Table 4-1 - TPS Run Summary, Mainline Express Train, Randolph Street to Harvey

Field Weakening	Maximum Speed Limit (mph)	Direction of Travel	Route Length (miles)	Trip Time (minutes)	Average Speed (mph)	Energy Consumption	
						kWh	kWh/car mile
Disabled	65	Outbound	19.95	38.77	30.87	568.61	4.75
		Inbound		41.07	29.15	550.96	4.60
Enabled	65	Outbound	19.95	36.99	32.36	681.39	5.69
		Inbound		39.46	30.34	646.34	5.40
Enabled	75	Outbound	19.95	36.80	32.53	700.68	5.85
		Inbound		39.16	30.57	684.03	5.71

[7] Metra Operations Profile, Electric District, April, 2000.

Table 4-2 - TPS Run Summary, Mainline Express Train, Randolph Street to Flossmoor

Field Weakening	Maximum Speed Limit (mph)	Direction of Travel	Route Length (miles)	Trip Time (minutes)	Average Speed (mph)	Energy Consumption	
						kWh	kWh/car mile
Disabled	65	Outbound	24.90	44.72	33.41	650.91	4.36
		Inbound		44.98	33.22	608.51	4.07
Enabled	65	Outbound	24.90	42.02	35.56	764.51	5.12
		Inbound		42.62	35.06	701.63	4.70
Enabled	75	Outbound	24.90	41.33	36.15	807.27	5.40
		Inbound		41.74	35.79	761.38	5.10

Table 4-3 - TPS Run Summary, Mainline Express Train, Randolph Street to University Park

Field Weakening	Maximum Speed Limit (mph)	Direction of Travel	Route Length (miles)	Trip Time (minutes)	Average Speed (mph)	Energy Consumption	
						kWh	kWh/car mile
Disabled	65	Outbound	31.08	53.31	34.98	793.75	4.26
		Inbound		54.16	34.43	706.95	3.79
Enabled	65	Outbound	31.08	49.34	37.80	935.97	5.02
		Inbound		51.77	36.02	804.06	4.31
Enabled	75	Outbound	31.08	48.33	38.59	969.91	5.20
		Inbound		50.39	37.01	876.77	4.70

The TPS results show that, once the field weakening is enabled, the rolling stock performance improves and its power consumption increases.

Detailed TPS results of the simulations for all station-to-station segments as well as for the whole route are presented in Appendix D.

4.4 ELECTRICAL NETWORK SIMULATIONS

4.4.1 Runs Performed

In order to establish the existing system capability to supply today's traffic density with the existing rolling stock, the ENS runs were performed for the train operational alternatives corresponding to the TPS runs presented above. These system simulations were performed with all substations in service and with the existing overhead catenary system configuration. The afternoon rush hour was simulated as it has the most onerous operation of the day.

4.4.2 Input Data

Input data were obtained from Metra drawings[8] and are presented in Appendix E.

4.4.3 Study Results

The results of the ENS runs are presented as follows:

- Distribution system voltage profile along the line.
- Highest RMS current in the catenary system.
- Substation power demands averaged over several time intervals.

4.4.3.1 System Voltages

Substations and paralleling stations should be located and rated so that under normal operating conditions, with all substations in service, all trains operate within the normal upper voltage and the normal lower voltage limits as shown in Appendix B. The traction power supply system voltages were used as an input to the computer simulations and the distribution system voltages were used as criteria to evaluate the simulated system performance.

The catenary system voltage profile for the existing system Mainline are presented for the following operating scenario in Figures:

- Existing System, Mainline, rolling stock field weakening disabled, maximum train operating speed 65 mph, Figure 4-1.
- Existing System, Mainline, rolling stock field weakening enabled, maximum train operating speed 65 mph, Figure 4-2.
- Existing System, Mainline, rolling stock field weakening enabled, maximum train operating speed 75 mph, Figure 4-3.

The South Chicago branch and the Blue Island branch with low speed operation were expected to yield satisfactory voltage profiles, and therefore only computer runs with field weakening enabled were performed to present the lowest voltages along the branches:

- South Chicago Branch, rolling stock field weakening enabled, maximum train operating speed 30 mph, Figure 4-4.
- Blue Island Branch, rolling stock field weakening enabled, maximum train operating speed 30 mph, Figure 4-5.

The charts show the voltages reached at vehicle pantograph and identify locations of low voltages along the route. The voltages for the existing operation along the Mainline with the field weakening

[8] Metra Engineering Department, DC Feeder Diagram, and Metra Electric District - BL-1063 Substations One Line Diagrams.

disabled and maximum train speed 65 mph, Figure 4-1, above the Normal Operating Voltage Limit of 1,200 V DC and, therefore, are satisfactory.

Once the field weakening is enabled, the voltages decrease below the Normal Operating Voltage Limit and below the Emergency Minimum Operating Voltage of 1,050 V DC, as illustrated by Figure 4-2. The Figure shows low catenary voltages at mileposts 3.03 and 22.54.

When the field weakening is enabled and the maximum train speed is raised to 75 mph, the voltage decrease below the Normal Operating Voltage Limit and below the Emergency Minimum Operating Voltage as shown in Figure 4-3. The Figure 4-3 shows low catenary voltages at mileposts 3.03, 13.05, 18.55 and 22.54.

The low voltages indicate that the trains are not receiving sufficient power. Performance degradation resulting in lower acceleration rates will likely occur.

Voltage profiles along the South Chicago branch, Figure 4-4, and the Blue Island branch, Figure 4-5 are satisfactory.

4.4.3.2 System Load Currents

The conductor currents calculated each snapshot were evaluated over the simulation interval as root-mean-square (RMS) values. The maximum load currents in the distribution system are presented in Table 4-5 and Table 4-6.

Table 4-5 - Maximum RMS Currents, Mainline

Field Weakening	Maximum Speed Limit (mph)	Maximum Current (A)	
		Calculated	Design Criterion
Disabled	65	592	1,870 A North of 63rd Street 1,700 A South of 63rd Street
Enabled	65	905	
Enabled	75	936	

Table 4-6 - Maximum RMS Currents, South Chicago and Blue Island Branches

Field Weakening Enabled	Maximum Speed Limit (mph)	Maximum Current (A)	
		Calculated	Design Criterion
South Chicago Branch	30	185	1,870 A
Blue Island Branch	30	135	

Comparison of the results of currents with the maximum allowable current derived in Appendix B reveals that the catenary system operates with a considerable margin of spare capacity, and that there is a little danger that the conductors would become overheated.

4.4.3.3 Substation Power Demands

Traction power substation average power demands were calculated and used to assess the system loading and to confirm suitability of the traction power substation ratings. The results are presented in Tables 4-7 to 4-9.

Table 4-7 - Maximum Substation Power Demands, Mainline Field Weakening Disabled, Maximum Speed 65 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion
Jackson	6	3.6	27	2.9	18	1.9	N/A	1.0	9
16th Street	10	6.7	45	5.5	30	3.3	N/A	1.8	15
Brookdale	8	7.1	36	5.8	24	4.0	N/A	2.1	12
Front Avenue	6	4.6	27	3.9	18	2.7	N/A	1.5	9
Harvey	4	4.3	18	3.4	12	1.5	N/A	0.9	6
Vollmer	4	2.7	18	2.1	12	1.1	N/A	0.6	6
Matteson	6	2.3	27	1.7	18	0.6	N/A	0.3	9
University Park	4	0.5	18	0.4	12	0.1	N/A	0.04	6

Table 4-8 - Maximum Substation Power Demands, Mainline Field Weakening Enabled, Maximum Speed 65 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion
Jackson	6	5.1	27	4.0	18	2.2	N/A	1.2	9
16th Street	10	9.0	45	7.3	30	4.1	N/A	2.2	15
Brookdale	8	8.2	36	6.7	24	4.8	N/A	2.5	12
Front Avenue	6	8.0	27	6.8	18	3.5	N/A	2.0	9
Harvey	4	4.3	18	3.7	12	2.0	N/A	1.1	6
Vollmer	4	3.1	18	2.6	12	1.4	N/A	0.7	6
Matteson	6	3.0	27	2.0	18	0.6	N/A	0.3	9
University Park	4	0.5	18	0.4	12	0.1	N/A	0.1	6

Table 4-9 - Maximum Substation Power Demands, Mainline Field Weakening Enabled, Maximum Speed 75 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion
Jackson	6	5.0	27	4.1	18	2.3	N/A	1.3	9
16th Street	10	10.0	45	8.2	30	4.3	N/A	2.3	15
Brookdale	8	8.5	36	7.3	24	5.1	N/A	2.7	12
Front Avenue	6	7.6	27	6.7	18	3.7	N/A	2.1	9
Harvey	4	4.2	18	3.4	12	2.1	N/A	1.2	6
Vollmer	4	3.3	18	2.6	12	1.4	N/A	0.7	6
Matteson	6	3.0	27	2.0	18	0.7	N/A	0.3	9
University Park	4	0.5	18	0.4	12	0.1	N/A	0.1	6

For the South Chicago and Blue Island Branches only the highest power demands are given in Tables 4-10 and 4-11. These occur for the condition of field weakening enabled and 30 mph operation.

Table 4-10 - Maximum Substation Power Demands, South Chicago Branch Field Weakening Enabled, Maximum Speed 30 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion
Jackson	4	0.09	18	0.03	12	0.004	N/A	0.001	6
Brookdale	4	2.5	18	1.2	12	0.5	N/A	0.2	6

Table 4-11 - Maximum Substation Power Demands, Blue Island Branch Field Weakening Enabled, Maximum Speed 30 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion	Calculated Value	Design Criterion
Front Avenue	4	0.40	18	0.10	12	0.01	N/A	0.002	6
Laflin	4	1.7	18	0.8	12	0.4	N/A	0.1	6

Comparison of the calculated power demands with the substation ratings indicates that all system substations operate well below their continuous and overload ratings.

4.5 TRACTION POWER SYSTEM AUGMENTATION

Enabling the field weakening has a significant impact on the traction electrification system operation. The ENS results reveal that the system now operates close to its capability and that once the field weakening is enabled and the maximum speed increased, the pantograph voltages would decrease below the Normal Lower Voltage Limit or the Emergency Minimum Operating Voltage. Therefore, additional computer simulation has been performed to study the effect of the electrification system augmentation.

In order to eliminate the low voltages, a computer simulation was performed with additional substations placed at the locations of low voltages. The augmented system voltage profile is shown in Figure 4-6. All voltages are above the Normal Lower Voltage Limit of 1,200 V DC which is satisfactory.

It is recommended that the new substations used for the system augmentation would be package-type units, completely assembled, wired, and tested in the factory. The substations would delivered to the selected sites as a single shipping units and would be installed onto a previously poured foundations and connected to the utility incoming circuits and the catenary feeders.

Comparison of the results of catenary currents, shown in Table 4-12, with the maximum allowable currents derived in Appendix B reveals that the catenary system operates with a considerable margin of spare capacity, and that there is little danger that the conductors would become overheated.

Table 4-12 - Augmented System, Maximum RMS Currents, Mainline

Traction Power System	Field Weakening	Maximum Speed Limit (mph)	Maximum Current (A)	
			Calculated	Design Criterion
Augmented	Enabled	75	808	1,870 A North of 63rd Street 1,700 A South of 63rd Street

Comparing the power demands with the substation ratings, as shown in Table 4-13, it can be concluded that all system substations operate well below their continuous and overload ratings. As shown in the Table, each substation would be rated at 2,000 kW. For this rating, one traction power transformer and one rectifier would be sufficient.

Table 4-13 - Augmented System, Maximum Substation Power Demands, Mainline Field Weakening Enabled, Maximum Speed 75 mph

Substation Name and Continuous Rating (MW)		Average Power Demands (MW)							
		15 Second		1 Minute		15 Minute		2 Hour	
		Calcula-ted Value	Design Criterion	Calcula-ted Value	Design Criterion	Calcula-ted Value	Design Criterion	Calcula-ted Value	Design Criterion
Jackson	6	3.7	27	3.2	18	1.8	N/A	1.0	9
16th Street	10	7.0	45	6.0	30	3.1	N/A	1.7	15
22nd/23rd Streets	2	7.4	9	6.2	6	4.2	N/A	2.2	3
Brookdale	8	4.8	36	4.2	24	2.3	N/A	1.3	12
103rd Street	2	2.3	9	1.8	6	1.0	N/A	0.6	3
Front Avenue	6	2.8	27	2.4	18	1.1	N/A	0.5	9
Riverdale Park	2	2.8	9	1.7	6	0.6	N/A	0.3	3
Harvey	4	0.5	18	0.4	12	0.1	N/A	0.04	6
172nd Place	2	3.5	9	3.0	6	1.7	N/A	0.9	3
Vollmer	4	2.6	18	2.4	12	1.3	N/A	0.7	6
Matteson	6	2.1	27	1.8	18	1.0	N/A	0.6	9
University Park	4	2.1	18	1.4	12	0.7	N/A	0.4	6

With limited site work, the package type substations are very economical. Section 12 presents the substation cost estimates.

5. CATENARY SYSTEM EVALUATION

5.1 EXISTING CATENARY SYSTEM

The existing catenary system used by Metra is of the compound catenary fixed termination type comprising single messenger wire, single auxiliary messenger wire, and two contact wires. The conductors are supported from large multi-track headspan arrangement structures and from pole-mounted cantilevers.

Chicago area ambient temperature extremes cause the tension of the overhead catenary conductors to vary widely. This results in a significant conductor sag in the summer and taut conductors in the winter. Converting the fixed termination system into an auto-tensioned system, which exhibits constant tension throughout the temperature range, will enable better contact wire-to-pantograph dynamic performance, decreased arcing, and improved current collection.

5.2 OPTIONS FOR CATENARY SYSTEM UPGRADE

In order to improve the pantograph to catenary interface and to reduce the possibility of contact wire breakage, Metra maintenance crews are periodically required to raise or lower tensions in different line sections depending upon the approaching season. This task is not simple to perform because of the number of contact wire clips and auxiliary clamps that need adjustment.

There are several options available to reduce the need for re-tensioning. Since the contact wire re-tensioning is more critical than the messenger and the auxiliary messenger wires re-tensioning, the following options were identified. The options are presented in order from lowest to highest cost.

5.2.1 Option 1: Optimizing Conductor Tensions

The conductor tensioning data currently used by Metra staff are assumed to be satisfactory for new conductors. Therefore, during re-tensioning, allowance needs to be made for the contact wire wear when selecting the conductor tensions. For example, Metra chart B-4579 states that the maximum contact wire wear is 45% of the original wire cross-section, but there is no indication as to what the corresponding worn wire tension should be.

As the contact wire wears, the wire loses tension, and any re-tensioning that needs to be performed should make due allowance for the wear, or the factor of safety would be eroded[9].

It is recommended that the criteria for re-tensioning of wires be reviewed and modified as appropriate to take into account the contact wire wear. Any future re-tensioning would be performed using the conductor tensions developed.

5.2.2 Option 2: Installation of Stronger Contact Wire

When it is time to renew the worn contact wire, a stronger contact wire can be installed. For example, silver-copper contact wire are about 10% stronger than normal hard-drawn copper wire, with no loss in conductivity.

It should be noted that the usual allowable wire wear value for contact wires is 25% to 30%. Metra's adopted value of 45% appears excessive for hard drawn copper, although it may be acceptable for a bronze wire.

5.2.3 Option 3: Lowering the Contact Wire and Changing the System Configuration

Lowering the contact wire height, but retaining the existing messenger wire height and reconfiguring the conductors would reduce the effects of temperature changes and equalize the contact wire tensions along the span. Since at some bridges and overpasses the contact wire height has been reduced to a height as low as 16 feet 6 inches, lowering the standard height of contact wire from 24 feet to 20 feet would still be acceptable from an operations point of view.

To achieve this in practical terms, it will be necessary to change to catenary system configuration to a single messenger and two 4/0 contact wires and dispense with the auxiliary messenger wire. The two 4/0 contact wires would be installed approximately 6 inches apart with separate hangers from the messenger[10]. This would be only possible on the South Chicago and Blue Island Branches where the voltage drop is minimal. On the Mainline, the two contact wires might need to be larger to restore the full system conductivity.

This proposal would include incorporation of a contact wire insulated overlap (CWIO) spans to replace the existing air-section-insulator (ASI) spans. Unlike the present ASI design, the contact wires in the CWIO would not be clamped together, but be independently supported from the

[9] Contact wire is normally designed to have tensions that provide a factor of safety of at least two in the worn condition.

[10] The experience of New South Wales Railway (NSWR) would help in the necessary redesign. The NSWR operates 1,500 V DC system with train speed of 100 mph on double contact wires spaced 6 inches apart.

messenger on their own hanger sets[11]. With an insulated overlap, each contact wire is alternately lifted out-of-running (*i.e.* non-running) with an in-line insulator cut-in at the supporting structure. For about one third of the span no hangers are needed to carry the weight since the wire is lifting at its own natural rise. Each non-running section of the overlap would act as a 'wire-reservoir', absorbing wire expansion and contraction, with less tension change than presently experienced.

Replacing the ASIs with CWIOs and separating the two contact wires throughout the tension section, would simplify maintenance and re-tensioning. In addition, it may be desirable, even necessary, to install contact wire registration arms at each structure.

5.2.4 Option 4: Introduction of Spring Tensioners

For increased control of tension in the contact wires it is feasible to install spring tensioners behind the cut-in insulators of the CWIO. By lowering the contact wires 4 feet, the hangers can be lengthened 4 feet which would allow the contact wires freedom to move independently of the messenger without being 'hung-up' by the hangers. Spring tensioners combined with fixed-terminated messengers have been installed on South African Railways for over 25 years.

Low bridges may require special new custom designs or may be treated as fixed points. If there are more than one low bridge in a tension section, the second, third, and each subsequent bridge support will need specially designed with hanger sets or to be fitted with resilient arms. Resilient arms are used at many bridges on the Metro-North conversion which was completed about 6 years ago. The replacement of a single tension section between two existing ASIs would appear practical, allowing train operation to resume immediately.

5.2.5 Option 5: Conversion to Auto-Tensioned System

The conversion from the existing fixed termination system to an auto-tensioned system can be performed under the following alternative scenarios:

- Auto-tensioning the existing conductors and increasing the main and/or auxiliary hanger lengths.
- Replacing some of the existing conductors and installing auto-tensioning.
- Installing an all-new auto tensioned system.

These alternatives would be expected to cost significantly more than the preceding Options. The description and discussion of these alternatives is deferred to Task 3.

[11] It may be necessary to introduce a second messenger in the CWIO. This would be achieved by using tension strain clamp or preformed deadend at each end of the CWIO and installing second messenger. This would result in half the tension on the existing messenger.

5.3 CONCEPTUAL DESIGN FOR AUTO-TENSIONING

5.3.1 Span Length Evaluation

For the system upgrade, span lengths should be examined and the conductor tensions evaluated with respect to conductor sag and blow-off under typical environmental conditions. The following issues should be considered in the system upgrade or conversion:

- Introduction of limited wire stagger on tangent tracks.
- Pantograph security analysis determining the minimum acceptable distance between a tip of the pantograph and displaced contact wire under most onerous weather conditions.
- Wire displacement due to cantilever swing and along-track conductor movement.

Curved track sections, in particular, may require additional catenary support structures to ensure that the contact wire remains within the "secure" region of the pantographs.

5.3.2 Wire Supports and Attachments along the Open Route

One important feature of the auto-tensioned system is the along-track movement of the overhead conductors due to temperature variation. The magnitude of the movement increases with distance from the tension section mid-point.

Wire support components such as steady arms, cantilevers, headspan wire assemblies, and wire clamps and jumpers must be designed to cope with this movement. Cantilevers should be mounted on hinged brackets and steady arms must be able to move with the contact wire. Similarly, messenger wire supports shall also allow for along-track movement.

In the event that the existing headspan arrangement would be reused, the messenger and contact wire supports need to be changed to provide for the required along-track movement of the conductors.

5.3.3 Wire Supports and Attachments under Bridges and Overpasses

Resilient arms designed for installation under the obstruction should be considered. The arms must allow for longitudinal conductor movement and provide vertical restraint.

5.3.4 Tension Lengths and Counterweights

At each end of the tension length, the overhead conductors are tensioned by counterweights via a set of pulleys. The maximum tension length for the auto-tensioned system is approximately one mile. Beyond one mile lengths conductor along track movement causes tension loss and stagger loss, both of which are unacceptable.

5.3.5 Mid-Point Anchors

Since the overhead conductors in an auto-tensioned system are free to move with temperature variation, mid-point anchors are required to stop migration of the entire section length of conductors in one direction. The overhead conductor movement is restrained at the span midpoint by clamps.

5.3.6 Contact Wire Grading

In areas where contact wire height is changing, it is important to grade the wire smoothly with respect to track to avoid excessive wire wear and arcing. The maximum contact wire gradient will be recommended for various track speeds using AREMA Manual for Railway Engineering, as follows:

- Transition shows:
  - 1 in 10*speed limit in mph
- Spans with constant contact wire gradients:
  - 1 in 5*speed limit in mph

The maximum acceptable wire slopes and gradients for various speeds are shown in the following table:

Table 5-1 - Contact Wire Gradients

Speed Limit (mph)		Maximum Gradients			
		First Span		Subsequent Spans	
From	To	Slope	Gradient (%)	Slope	Gradient (%)
0	10	1 in 100	1.00	1 in 50	2.00
10	20	1 in 200	0.50	1 in 100	1.00
20	30	1 in 300	0.33	1 in 150	0.67
30	40	1 in 400	0.25	1 in 200	0.50
40	50	1 in 500	0.20	1 in 250	0.40
50	60	1 in 600	0.17	1 in 300	0.33
60	70	1 in 700	0.14	1 in 350	0.29
70	80	1 in 800	0.13	1 in 400	0.25

5.3.7 Sectionalizing

In order to preserve the present electrical sectioning, overlaps of the auto-tensioned system will be located at the present air breaks. Additional air breaks can also be designed into an auto-tensioned system for intermediate sectioning points.

5.4 FACTORS INFLUENCING SYSTEM UPGRADE

Factors influencing the selection of the future catenary system configuration include:

- Reduction of the overall system copper cross-sectional area would be only possible on the South Chicago and Blue Island Branches where the voltage drop is minimal. On the Mainline, where the system operates at the margin, this would be possible only in the event that the electrification voltage is increased to 12.5 kV or 25 kV. Increasing the electrification voltage would also decrease the system losses.
- Replacing of the existing double contact wires with a single, but larger contact wire, would improve commutation and reduce maintenance associated with the existing double contact wires. However, it would be necessary to replace the existing air-section-insulators with contact wire overlaps or air breaks.
- Age and serviceability of the existing conductors may accelerate the decision to system conversion.
- In the event that, as expected, the train services will expand in frequency to meet growing passenger demand, there will be fewer windows and of shorter duration for new construction, after the needs for maintenance have been programed.

The major factors influencing the decision whether to convert to auto-tensioned catenary system also include availability of funds for conversion and integration with the technical and financial policies of the South Shore Line.

6. SIGNAL SYSTEM

6.1 SYSTEM EVALUATION

The existing signal system will be evaluated in the following subdistricts:

- Mainline (University Park Subdistrict)
- South Chicago Subdistrict
- Blue Island Subdistrict

Also, the major system interlockings will be discussed.

6.2 MAINLINE

The Mainline signal system starts south of 11th Place which is currently controlled by switch tenders. This location should eventually be made an interlocking and be controlled from the CCF.

The existing signal system is single direction, running from approximately Milepost 2 to Kensington, Milepost 14.21[12]. Tracks 1 and 2 are normally used for southward operation and Tracks 3 and 4 for northward operation. Track 1 is signaled for bi-directional operation between 67th Street and Kensington.

There are current Metra projects to replace the existing single direction Automatic Block Signal (ABS) from Control Point (C.P.) 1.34 to 65th Street and from C.P. 69th Street to Kensington with a bi-directional signal system. This project will also replace the existing aging AC track circuits with new electrified Electro Code (E^2 Code) equipment. The E^2 Code will provide more reliable track circuits, replace line wires that control "H" and "D" relays, and would enable train operation up to 69 mph on all four tracks to Kensington.

South of Kensington, the Centralized Traffic Controlled (CTC) system is installed from Milepost 15.21 to Richton on Tracks 1 and 2. Richton to University Park system is single track controlled by CTC from the CCF. Additionally, there is a small section of E^2 Code at Matteson.

There are no at grade crossings on the Mainline.

[12] All mileposts were obtained from the current Electric District timetable dated 5/2/99.

6.3 SOUTH CHICAGO SUBDISTRICT

The South Chicago subdistrict is a double track system, single direction, equipped with ABS from 67th Street to 90th Street. Maximum speed is 30 mph. There are no interlockings in this district. There is one spring switch near 90th Street, one hand-throw crossover near 82nd Street, and two hand-throw crossovers near 74th Street.

There are 36 at-grade crossings equipped with gates and flashing warning devices. When the 93rd Street Station will open, the new section of track will add two more at-grade crossings. The South Chicago subdistrict signal system is out of date, but is well maintained. The system along the branch has been upgraded to some degree, but needs to be refurbished with newer types of equipment as the existing AC vane relays can no longer be purchased. Most of the at-grade crossings in this district also include pedestrian gates.

6.4 BLUE ISLAND SUBDISTRICT

The Blue Island subdistrict is a single track system operating at maximum speed of 30 mph from Kensington, Milepost 15.60 to Blue Island Coach Yard, Milepost 18.91. The signaling system is of the Controlled Block System (CBS) type.

At West Pullman siding, Milepost 16.56, spring-operated switches are installed at both ends of the siding. There is a northward and southward main track at this location.

The Blue Island subdistrict has 27 at-grade crossings, but not all of these crossings are protected with gates. Metra has an ongoing project to add gates to the unprotected crossings.

6.5 INTERLOCKINGS

The following interlocking will be evaluated:

- Randolph Street controlled from Randolph Tower
- 51st Street controlled from 67th Street Tower
- 67th Street controlled from 67th Street Tower
- Kensington controlled rom Kensington Tower
- Homewood controlled from Consolidated Control Facility (CCF)
- Richton controlled from Consolidated Control Facility (CCF)
- University Park controlled from Consolidated Control Facility (CCF)
- Harvey controlled from Consolidated Control Facility (CCF)

6.5.1 Randolph Street

The Randolph Street interlocking was installed in 1987 with Union Switch and Signal (US&S) equipment and is now controlled from the CCF. There are 37 100 Hz phase selective units (PSUs) that drive a code-following relays. The equipment may be used in 25 Hz or 60 Hz electrified territories. This track circuit arrangement is still available by the manufacturer for maintenance replacement.

There are 34 M3-type switch machines used in single switch turnouts and double slip switch layouts. The switch machine parts are available from US&S. The equipment controlling the control machines Genisys non-vital and vital relays are also available from the manufacturer.

6.5.2 51st Street

The 51st Street interlocking is remotely controlled from 67th Street Tower. Part of Metra's ongoing improvement plan is to retire 51st Street Interlocking and to put a new Interlocking at 45th Street with the latest technology to be controlled from the CCF. The existing equipment at 51st Street includes GRS plug-in type relays and GRS Model 5A switch machines which are still available from the manufacturer.

6.5.3 67th Street

The 67th Street Interlocking was installed in 1925. Metra is currently planning to replace 67th Street Interlocking with facilities which will be called C.P. 65th, 67th, and 69th.

6.5.4 Kensington

The Kensington interlocking was installed in 1984 using GRS equipment[13]. The control machine at Kensington is a GRS Micro Traffic Master Centralized Traffic Control System. The Kensington interlocking incorporates 26 (15 on Metra and11 on NICTD) GRS 200 Hz phase selective track circuits, vital plug-in relays, and 37 switch machines. All equipment is still available from the manufacturers.

6.5.5 Homewood, Richton Park, University Park, and Harvey

Homewood has two universal crossovers, Richton Park has two crossovers and one turnout, and University Park has one turnout. In addition, there is one hand-throw crossover at Harvey. The equipment is currently controlled from the CCF. All equipment was installed in the 1980's and is still available from the manufacturer.

[13] There is a study being performed for NICTD on train movements through Kensington.

7. COMMUNICATIONS SYSTEM

7.1 SYSTEM EVALUATION

The existing communications systems, including the Supervisory Control and Data Acquisition (SCADA) system, voice communication systems, and fiber/copper backbone systems, will be assessed with regard to technology used, future maintenance costs, and its capacity to meet future operating requirements and changes with respect to the traction power system.

7.2 SCADA SYSTEM

A new SCADA system for monitoring and controlling the traction power substation electrical equipment, monitoring of substation fire alarms, and monitoring of doorway intrusion alarms is being installed on the Metra Electric District as shown on SCADA System Interconnection Block Diagram, Drawing F-1, Appendix F.

The SCADA equipment cabinets installed at substations are currently being tested back to the Main SCADA System equipment at the CCF via the existing Ameritech leased data circuit. Cable junction boxes with 25 pair telephone cables have been installed from the Metra Electric District right-of-way to the outside wall of the substations. These telephone cables are terminated within the substations for the new SCADA system data circuits and substation telephone lines as shown on the Metra Substation SCADA RTU Circuit Network Cable Connections shown on Drawing F-2, Appendix F.

7.3 COMMUNICATIONS BACKBONE

The new SCADA system will be connected to the CCF via two telephone data circuits, SCADA Main and SCADA Backup. One data circuit will be the currently leased Ameritech data circuit and the second data circuit will be a channel in the existing Electric District Fiber Optic Transmission System with microwave link back to the CCF.

The connection of the new substation SCADA equipment to the existing Metra fiber optic backbone system will be via the newly installed Metra telephone cable between the substations and the Electric District railroad as shown on Microwave/Fiber Optic OC-3 Network Diagram, Drawing F-2, Appendix F and on South Electric District Fiber Optic and Copper Cable Network, Drawing F-3, Appendix F.

7.4 COMMUNICATION PROVISIONS FOR PROPOSED SUBSTATIONS

The existing and upgraded Metra fiber optic transmission system OC-3 and the telephone system are already sized to accommodate the type of expansion recommended in this report. In the event that the proposed four new substations are implemented by Metra,, each of the new facilities will require the following communication system equipment:

- SCADA cabinet assembly with modems.
- Pyrotronics System 3 fire alarm panel monitored remotely at the Randolph Street Control Room via a leased Ameritech telephone.
- Telephone instrument connected to Metra via a telephone DS-O channel in the fiber optic OC-3 Transmission System or a leased telephone line from Ameritech.
- CCTV System installed for local security purposes consisting of a camera located at each outside entrance wall for viewing the Substation street doorway entrance and a CCTV monitor located just inside the entrance. A similar CCTV Camera/Monitor system shall be installed at the rear wall for monitoring the alley entrance.
- Door intrusion circuits installed at each entrance.

8. STORAGE AND MAINTENANCE FACILITIES

8.1 LOCATION AND CAPACITY

Ideally, transportation planners prefer to place storage locations in a secure areas at or near the end of a service line. Positioned such, non-revenue equipment moves are minimized. The locations, cars stored, and functions performed in the Metra Electric District storage yards and maintenance facilities are discussed below.

Trains terminating their morning rush service at Randolph Street Station use the 18th Street Yard for a mid-day layup. Located at Milepost 1.8, it is quite close to the station, and no improvement in location are unlikely. The Millennium Project construction and enclosing of tracks just south of Randolph Street Station further limits operating practices and possible locations for temporary layups. Additionally, 22 cars tie up Track 4 at van Buren Street during mid-day hours.

The three yards at the south end of the Electric District, Blue Island, Matteson/Richton Park and University Park, have different configurations of track, and train service patterns. The yards are in locations where service begins, and well positioned to minimize empty equipment moves. Every available yard track is occupied during overnight layover and the only available capacity for growth is to accommodate longer trains or add tracks.

Metra's strategy for meeting passenger growth is to increase the number of cars on trains to an even number, and to add longer trains at the "shoulders" of the rush hour[14]. In Task 3, any extra capacity at the storage yards that might be required to accommodate future growth will be assessed.

Weldon (18th Street Storage Yard) shop has several significant problems that cannot be rectified by remodeling. These include:

- Severely undersized storage room.
- Poor street access for delivery of parts and materials.
- The shop tracks cannot hold a complete 6-car train.
- Work pits under the cars are too shallow and poorly lit.
- Inadequate space for component repair shops.

Metra currently has a consultant under contract to develop conceptual plans of a yard and shop at other locations and is evaluating potential sites.

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[14] There are only a few platforms long enough to accommodate 7-car trains, and the 211th Street Station is the only one that will hold 8-car trains.

8.2 OPERATION PRACTICES

A cursory inspection of the storage yards and maintenance shops operations practices was performed from the following perspectives:

- Transportation Operation
- Car Maintenance Program
- Periodic Inspection
- Car Cleaning
- Execution of the Maintenance Program
- Time Requirement
- Maintenance Efficiency

8.2.1 Transportation Operations

The trains are stored overnight in the yards discussed above, except for the 18th Street and KYD yards. Engineers and conductors report for work at the yards, ready their trains for service, and move the trains to the platforms for passenger loading. The trains then enters revenue service. The procedure is simple and efficient.

If the consist requires a mid-day layover at 18th Street Yard, the crew or a relay crew will move the consist to the yard. Six relay crews plus two pilots are assigned to Randolph Street Station and four relay engineers and three pilots are assigned to 18th Street Yard for handling the local equipment moves.

8.2.2 Car Maintenance Program

The Mechanical Department, through its maintenance and cleaning activities on the cars, presents the Metra image to the riding public. The cars are the most recognizable feature of the system, and play an important role in shaping the public perceptions and riding habits. The Mechanical Department has set up inspection, preventive maintenance, overhaul and cleaning programs to preserve the cars' performance, comfort levels, and appearance. The execution of this maintenance program is carefully scheduled to allow 170 daily trains to run.

8.2.3 Periodic Inspections

The core of the maintenance program are the periodic inspections (PI). Most of the PIs are mandated by the Federal Railroad Administration (FRA). Since the Highliners are all self-propelled vehicles, the FRA treats them as a locomotive when interpreting the rules and regulations. The PIs performed by the Metra Mechanical Department are listed in Table 8-1.

Table 8-1 - Periodic Inspection Schedule

Frequency	Name
Every day	Daily Inspection, done at Randolph St. Station, Van Buren/4 Main, and 18th Street Yard
Every 45 days	45-day Inspection, done at 18th Street Shop
Every 92 days	Quarterly Inspection, done at 18th Street Shop
Every 6 months	Semi-annual Inspection, done at 18th Street Shop
Every year	Annual Inspection, done at 18th Street Shop
Every 2 years	Bi-annual Inspection, done at 18th Street Shop
Every 3 years	Tri-annual - Done at KYD Shop

All but the 45-day inspection are FRA-mandated inspections. The scope of maintenance work grows at each maintenance visit. For example, the number of work items shown on a checkoff sheet for performing the 45-day inspection is 40, and this raises to 88 work items for the annual inspection. The checklists for the bi-annual and tri-annual inspections were not provided to the consulting team.

This type of maintenance program is very similar to programs in use at other passenger railroads around the United States.

8.2.4 Car Cleaning

The interior of the cars are cleaned at all maintenance locations except KYD. Cleaning is done during the first shift while the cars are on mid-day layover at Randolph Street Station and 18th Street Yard. Night time (3rd shift) cleaning is done at the yards located at the southern end of the Electric District.

Only one facility, the Weldon/18th Street Yard, is equipped to perform exterior train washing. The car wash is located outdoors on the east side of the Weldon Shop. The facility can wash up to 6-car train consists. The train is run past two sets of electrically operated rotating brushes located on both sides of the track. One set of the brushes provides "pre-soak" and the other provides "scrubbing". Once a train is washed, it is run in a reverse direction to be rinsed.

An operator located in a glass-enclosed cubicle outside of the shop building can remotely control the car wash operation. If needed, the movement of train back and forth can be repeated to ensure clean cars. Procurement of a new car washer is recommended for the Metra Electric District.

8.2.5 Execution of the Maintenance Program

Cars about to receive PI are placed on Track 1 in the 18th Street Shop. All PIs are performed on the first shift which operates from 7:40 AM to 3:40 PM. When the Track 1 is full, the additional cars would be put on Track 2. Normally, cars would occupy the shop track for the duration of the shift. Some of the less intensive PIs don't require a full eight hours to perform, but the crews usually find some running repairs that need performing, and they are handled while the car is in the shop.

At the end of the shift all cars on Track 1 are coupled and moved into the yard to await return to service as a complete train consist. Likewise, the cars on Track 2 will be coupled and made ready for service.

Cars that require running repairs are spotted on tracks 3 and 4 in the shop, and upon completion of those repairs, the cars are individually put back on storage tracks where needed to complete the required consist makeup.

8.2.6 Time Requirement

A full 8-hour shift is scheduled to perform a PI. While smaller-scope inspections require less time, there are generally some light repairs on cars that are found and must be handled.

The maintenance and storage facilities in the Metra Electric District are shown in Table 8-2. Each facility has a mix of personnel according to the needs of the maintenance program and operating plans at the location. The mechanical work force work the shifts as shown in Table 8-2.

Table 8-2 - Shifts Worked-Mechanical Forces at Various Locations

Location	Shifts Worked-Mechanical Forces		
	Day	2nd	3rd
Randolph Street (North Terminal, including 4 main)	x	x	x
Weldon/18th Street Yard	x	x	
Kensington Yard (KYD)	x		
Blue Island Yard			x
Matteson/Richton Park Yard			x
University Park Yard (South Terminal)			x

8.2.7 Maintenance Efficiency

A cursory review of maintenance efficiency was performed. In order to assess the efficiency level, benchmarking was chosen for this examination. For more accurate evaluation, a higher level of effort would be required, so that every maintenance operation can be studied either by continuous observation or by work sampling.

Maintenance efficiency can be measured as a ratio of number of employees required per vehicle maintained. Metra's Electric District ratio is 0.77 employees/vehicle. Long Island Rail Road's ratio is 1.25 employees/vehicle, and Metro-North Railroad's ratio is 0.74 employees/vehicle. This method does not represent a definitive measure of mechanical efficiency, as fleet mileage, type of vehicles, amount of work contracted to vendors, and the amount of heavy overhaul programs performed vary from railroad to railroad. The ratio indicates, however, that Metra maintenance staffing levels are in a reasonable range.

9. LIGHT AND POWER TRANSMISSION LINES

9.1 PURPOSE OF LINES

The existing Metra Electric System includes light and power (L&P) transmission lines along the right-of-way. The lines receive power from the Metra traction power substations and the local electric power utility, Commonwealth Edison Company. The purpose of these transmission lines is to deliver power to various Metra facilities including signal system, passenger stations, and maintenance facilities. The lines provide Metra with reliable and flexible sources of power along the right-of-way.

9.2 LINE REHABILITATION PROGRAM

Metra is presently engaged in an ongoing rehabilitation program of the (L&P) transmission lines along Electric District Mainline, South Chicago and Blue Island Branches. These upgrades and enhancements are necessary to maintain the operation the transportation system originally installed and put into operation approximately 75 years ago.

Based on visual inspections of representative sections of the L&P transmission system and discussions with Metra technical staff personnel, it was concluded that the L&P transmission system is operating satisfactory at present.

To date, various items of the L&P transmission system equipment housed in the existing traction power substations have been replaced and/or enhanced as discussed below:

- Step-down transformers filled with PCB cooling fluids have been replaced with new dry type or non-PCB filled transformers.
- New 5 kV distribution switchgear has replaced older and obsolete circuit breakers.
- Distribution disconnect switches have been upgraded or replaced.
- Substation feeder cables feeding the L&P overhead distribution connection points have been replaced with new non-lead covered cables.
- The old L&P power distribution monitor/control systems have been replaced. The new supervisory control and data acquisition systems (SCADA) were initially installed during the 1960's. Upgrade and enhancements to the SCADA systems are being done continually as a part of the on-going Metra rehabilitation program.

Along the system right-of-way, the distribution conductors are being upgraded. The system conductors, insulators, spacers and associated supports are being replaced by Metra personnel. To

date, the Blue Island Branch has been completed and work continues on the South Chicago Branch. Also, some spot replacement has been performed along the Mainline system.

9.3 LINE LOADING

The average connected L&P subsystem power loads were obtained through research of the Metra Electric District reference materials as shown in Table G-1, Appendix G. The values are only approximate, as the actual connected power load varies from day to day, week to week, and month to month, as equipment is connected to and disconnected from the lines.

At present, the transmission line circuits are relatively lightly loaded as shown in Tables G-2 and G-3, Appendix G. Following review the existing and the future L&P circuit installation details, it is apparent that an increased level of loading in the future should not impact the overall Light and Power Transmission System integrity.

In the near future, Metra will be able to determine L&P power loadings more accurately via their upgraded SCADA system. The SCADA system will provide actual "real-time" power load metering which can then be compiled into daily, weekly, and yearly records. When this data are available, it is recommended that Metra performs an in-depth analysis of the transmission line voltage drops and load currents under all substations in service condition and for substation outages.

10. SUBSTATION REAL ESTATE REQUIREMENTS

10.1 NEW FACILITIES

The traction power load-flow simulations identified a need for four additional traction power substations. The substation sites are identified in Table 10-1.

Table 10-1 - Locations of Proposed Substations

Substation Milepost	Substation Location
3.03	Triangular parcel of land in the vicinity of 22nd and 23rd Streets, on the west side of the tracks.
13.05	Rectangular parcels of land on north and south side of 103rd Street, on the west side of the tracks.
18.55	End of Riverdale Park at 146th Street and Eggleson Avenue, on the west side of the tracks.
22.54	Area along the ROW at 172nd Place, on the west side of the tracks.

10.2 REAL ESTATE SIZE

Package-type traction power substations are compact in size. The housing dimensions are approximately 16 feet x 42 feet for a four feeder substation serving two tracks to 16 feet x 50 feet for an eight feeder substation serving four tracks. Depending on site specific location, additional allowance may be required for access road and parking.

10.3 SITE ASSESSMENT

All four potential sites were visited and deemed to be suitable for the proposed substation installations.

11. ENVIRONMENTAL IMPACT OF NEW SUBSTATIONS

The environmental impact of the new substations will be relatively minor. The substations are normally designed and built in relatively compact metal prefabricated housings. However, the metal housings can be further architecturally treated and supplemented with various types of finishes matching the surrounding buildings. Also, provision of trees and shrubs in the substation vicinity provides an effective screen.

During a preliminary engineering, a conceptual equipment layout of the substations should be developed together with the site dimension requirements. The available real estate along the right-of-way needs to be identified and the potential sites assessed. The site assessment process normally includes resolving of number of environmental issues, determination of likely property costs, evaluation of adjacent land uses, assessment of existing soil conditions including occurrence of hazardous materials, locating wetlands, appraisal of local land acquisition requirements, and determining cost effectiveness of utility connections.

Local governing agencies should be contacted during the site assessment period to fully coordinate utility, zoning, building, and landscape requirements. The actual site visits are always key activities contributing to the decision making process for evaluating issues such as site impact to the adjacent properties and site accessibility.

12. NEW SUBSTATION COST ESTIMATE

12.1 LEVEL OF COST ESTIMATE DETAIL

The proposed Metra electrification system augmentation consists of four traction power substations. The substation cost estimates were broken down into equipment groups as required for each construction location. Appropriate add-ons were included such as engineering, construction management, contractor's mobilization and demobilization, Metra's force account, spare parts, special tools and equipment, training and manuals, construction contingency, escalation, and any other appropriate cost items identified during the course of the project.

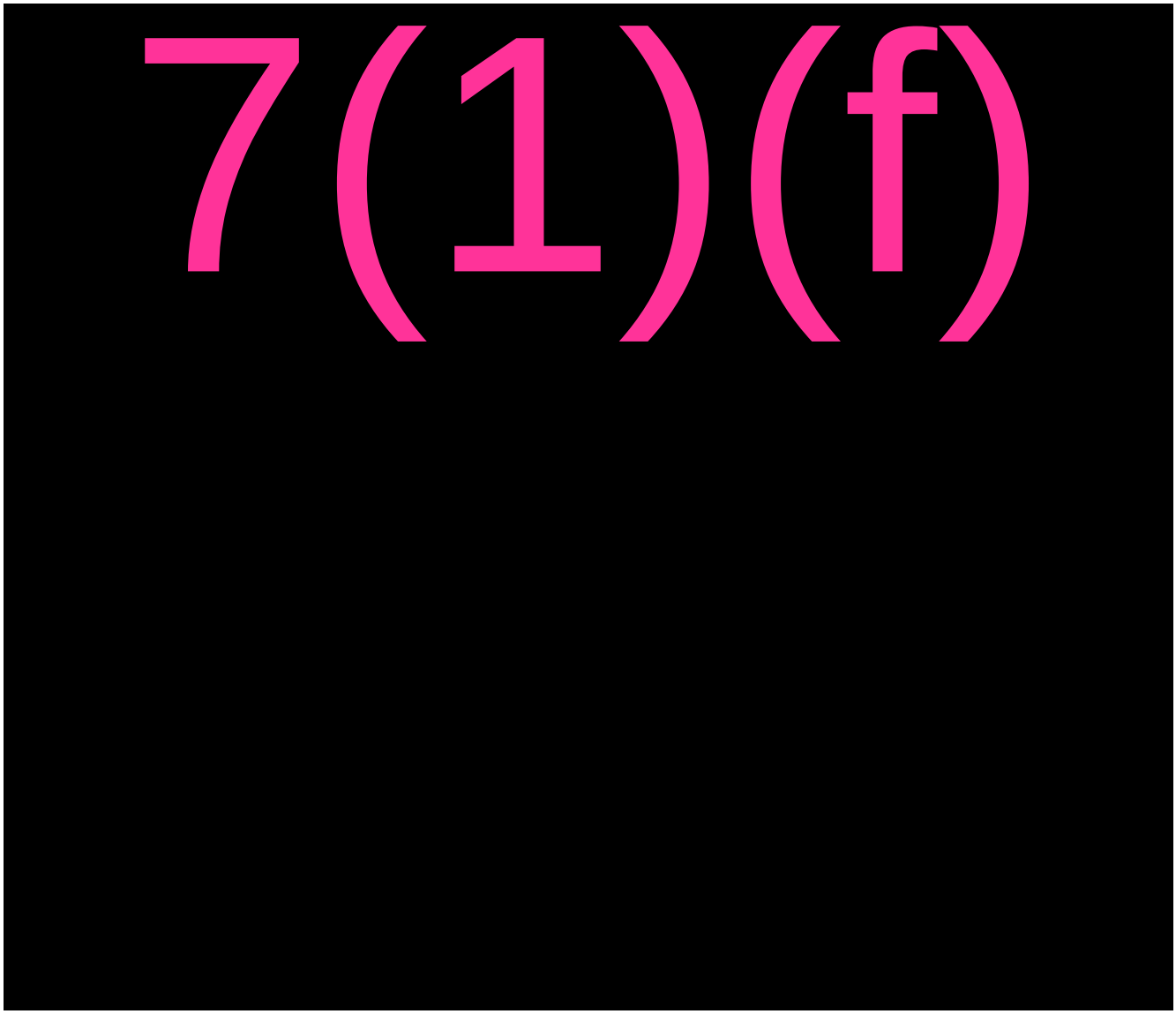
12.2 COST ESTIMATE PRESENTATION

The substation cost estimates were prepared on computer-generated spreadsheets organized by each new facility type proposed. This setup enables Metra to update the estimates in the future as the study progresses to design, preliminary engineering, final engineering, and as more detailed information is available.

In Appendix H, cost estimates for a typical eight-feeder substations serving four tracks and four-feeder substations serving 2 tracks were developed. A summary sheet combining two of each substation type yields a total cost of approximately $7 million.

13. RECOMMENDATION AND IMPLEMENTATION

Based on the foregoing discussion and cost estimates, the following conclusions and recommendations can be made.



Appendix A - TERMS AND ABBREVIATIONS

A.1 GLOSSARY OF TERMS

Ampacity. Current-carrying capacity of a conductor, expressed in amperes.

Auxiliary Messenger Wire. Wire supported by the messenger which in turn supports the contact wire. The wire also acts as an auxiliary current conductor.

Catenary System. Overhead power distribution system providing traction power to electric locomotives and MU cars.

- Compound Catenary System - a system of messenger wire supporting an auxiliary messenger wire by the means of hangers which, in turn, support a contact wire by parallel groove clamps. The system is suitable for high speed application.
- Simple Catenary System - a system of messenger wire supporting a contact wire by the means of hangers. The system is suitable for medium speed to high-speed applications.

Catenary System Supporting Structures. Poles, towers, bridges, or other stationary structures used for supporting a catenary system including foundations, anchors, guys, braces, and similar reinforcing attachments.

Centralized Electrification Traffic Control (CETC) System. Computer-based system used for controlling operation of the traction power system and movements of trains.

Component. Item of complete hardware as commonly supplied by manufacturers.

Conceptual Design. A generalized plan describing design requirements and used as a guide to preliminary design.

Contact Wire. Conductor in contact with pantograph used by locomotives and MU cars to collect train power requirements. The conductor is suspended from messenger or auxiliary messenger by the means of hangers and contact wire clamps.

Contact Wire System. Overhead power distribution system providing traction power to electric locomotives and MU cars.

- Single Contact Wire System - a system of single contact wire without messenger or auxiliary messenger wire. The system is suitable for yard and shop applications.
- Twin Contact Wire System - a section of system where a contact wire is spliced into a messenger wire. The two contact wires are installed side by side and supported by insulated

supports attached to the underside of a structure, such a overhead bridge. The system is used in areas where the vertical clearance does not allow the use of compound or simple catenary systems. The system is suitable for medium speed to high-speed applications.

Directive Drawings. Drawings defining general arrangements or configurations of facilities for a particular project.

Disconnect Switch. A device used for disconnecting of de-energized items of equipment and sectioning of catenary system. Disconnect switches do not have a fault breaking capability, but may have some load breaking capability.

Distribution. Delivery of power from transmission system to an end-use customers at voltages greater than 110 V and less than 69 kV.

Electric Traction. A means for propulsion of railroad vehicles whereby power is provided by electrical energy transmitted from a remote source through a catenary system.

Final Design. A design stage during which final specifications, contract drawings, schedules, and cost estimates are prepared for specific construction project.

Frequency Converter. Frequency converter used for electrical traction purpose converts three-phase utility power of one frequency to single-phase power of different frequency.

- Rotary - Converter comprised of a three-phase motor and a single-phase generator.
- Static - Converter using semiconductor devices such as thyristors.

Grounded Equipment. Equipment connected to the conducting mass of the earth via ground rods, grounding grid or both to ensure an immediate discharge of electrical potential without danger.

Harmonics. Voltages and currents at frequencies other than the fundamental system frequency. Harmonics are caused by non-linear circuit components such as thyristors.

Harmonic Distortion. Due to the harmonic currents generated by thyristor-controlled equipment on board the rolling stock or in substations, the utility and traction voltage and current waveforms are not sinusoidal.

Impedance Bond. An iron-core coil of low resistance and relatively high reactance used to confine signaling current to its own track circuit and to provide a continuous path for the traction return current around insulated joints to substation.

Messenger Wire. Upper wire in a catenary system from which the contact wire is suspended by means of hangers.

Milepost. An identifier for a given location along a railroad line. Mileposts may or may not be located exactly one mile apart and may not be sequentially numbered.

Multiple-Fed System. Electrification system in which substations feed sections of catenary at multiple points. All conditions being equal, the multiple-fed system exhibits lower catenary voltage drop than the center-fed system. The system substations can have several traction power transformers or SFCs and operate with the substation low voltage bus-tie circuit breaker normally closed. Multiple-fed systems do not usually operate at commercial frequency because the entire system must be supplied at the same phase.

Power Demand Analysis and Load-Flow Study. A computer-aided study using specially written computer program to calculate the combined performance of the traction power supply and traction power distribution systems with operating trains. The study results include catenary system voltages, catenary system currents, substation power demand requirements and substation energy consumption.

Power Factor. Ratio of useful (real) power to total (apparent) power. Power factor is dependent on the locomotive propulsion system and substation converter design. Generally, the power factor is low at low trains speeds and improves as the speed increases.

Power Transmission Factor. Ratio of transmitted power to power transmission capability.

Preliminary Design. A design stage at which specifications and drawings clearly show all major design elements and define requirements for final design. Design calculations are substantially complete, cost estimates are detailed to an extent compatible with the level of design, and a preliminary construction sequence schedule is prepared.

Span. Distance between catenary system structures.

- Length - Along track distance between structures.
- Width - Across track distance between the poles of a cross-span or headspan.

Station Dwell Time. That amount of time during which a train is stopped to open and close doors and receive and/or discharge passengers.

Substation. Traction power supply facility. Typical traction power substation includes power utility interface equipment, disconnect switches, circuit breakers, traction power transformers, switchgear, control equipment, signal power supply equipment, and auxiliary system. Special equipment, such as harmonic filtering and power factor control equipment, may be installed in substations as required. Substations serving electrification systems operating at other than commercial frequency also contain frequency converters.

Switching Station. Station containing circuit breakers or switchgear line up. Switching stations are located between substations and are used in AC electrification systems for switching section of distribution system during substation outage conditions and for paralleling of distribution system circuits.

Tie Station. Stations containing circuit breakers or switchgear line up. Tie stations are located between substations and are used in DC electrification systems for paralleling of distribution system circuits.

Traction Electrification System. Traction power supply and traction power distribution systems.

Traction Power Supply System. Traction power substations located at predetermined spacings along the route.

Traction Power Distribution System. Overhead catenary system or contact wire system which may be accompanied by overhead or underground along track feeders.

Trade-Off Analysis. A study of selecting a specific project alternative objectively considering all aspects related to all alternative methods of accomplishing the same action or an acceptable alternate action. Considerations include technical evaluations, environmental impact evaluations, and assessment of comparative costs.

Train Performance Simulator (TPS). A computer program representing operation of trains based upon tractive effort of the power units, resistance of the train to motion, and railroad alignment characteristics. TPS can calculate time, distance, speed, acceleration, power demand, energy consumption and loss relationships of a train for all station to station runs and for the whole route.

Transformer Cooling Class.

- OA - Self-Cooled
- FA - Forced-Air-Cooled
- FOA - Forced-Liquid-Cooled

Transmission. Delivery of power at a voltage of 69 kV or higher from generating units across interconnected high voltage facilities to points where the power enters distribution system.

A.2 LIST OF ABBREVIATIONS

A	Ampere
AAR	American Association of Railroads
A, B, C	High voltage system phase designations
AC	Alternating Current
ACSR	Aluminum Cable Steel Reinforced
APTA	American Public Transportation Association
AREMA	American Railway Engineering and Maintenance-of-Way Association
AW0	Weight of empty, ready-to-run vehicle
AW1	Weight of vehicle with full seated load
AW2	Weight of vehicle with design load
AW3	Weight of vehicle with full load
AW4	Weight of vehicle with crush load
cmil	Circular mil
CN	Canadian National

DC	Direct Current
EIS	Environmental Impact Statement
EMI	Electromagnetic Interference or Electromagnetic Induction
EMM	Energy Management Model
ENS	Electric Network Simulator
EPR	Ethylene Propylene Rubber
ESI	Electrostatic Interference or Electrostatic Induction
FA	Forced-Air-Cooled
FOA	Forced-Liquid-Cooled
HV	High Voltage
Hz	Hertz
IGBT	Insulated Gate Bi-polar Transistor
ICRR	Illinois Central Railroad
kA	Kiloampere
kcmil	Kilo circular mil
kV	Kilovolt
kVA	Kilovolt-Ampere
kVAr	Kilovolt-Ampere Reactive
kW	Kilowatt
kWh	Kilowatt-Hour
LV	Low Voltage
MA	Motor-Alternator Set
M/G	Motor-Generator Set
MV	Medium Voltage
MVA	Megavolt-Ampere
MVAr	Megavolt Ampere Reactive
MW	Megawatt
MWh	Megawatt-Hour
N. C.	Normally Closed
N. O.	Normally Opened
non-RR	Non-railroad, not belonging to railroad
OA	Self-Cooled
O&M	Operation and Maintenance
p. u.	Per Unit
RMS	Root-Mean-Square

ROW	Right-of-Way
RR	Railroad
SCADA	Supervisory Control and Data Acquisition
TPS	Train Performance Simulator
V	Volt
XLPE	Cross-Linked Polyethylene

Appendix B - STUDY CRITERIA

B.1 SYSTEM VOLTAGES

The American Railway Engineering and Maintenance-of-Way Association (AREMA)[15] defines the following standard voltages:

- **Nominal Operating Voltage** - voltage measured at the pantograph of a train located at the substation feed point while full rated power is being drawn from the appropriate substation transformer or transformers if connected in parallel.
- **Normal Upper Voltage Limit** - voltage measured at the pantograph of a train located at the substation feed point with no traction power being drawn from the appropriate substation transformer or transformers if connected in parallel. The Normal Upper Voltage Limit is 110% of the Nominal Operating Voltage.
- **Normal Lower Voltage Limit** - voltage measured at the pantograph of a train located at the point of maximum voltage drop with the catenary functioning for normal design conditions assuming no substation outage and rated continuous power being developed by the rolling stock. The Normal Lower Voltage Limit is 80% of the Nominal Operating Voltage.
- **Emergency Minimum Operating Voltage** - voltage measured at the pantograph of a train operating under emergency conditions, such as substation outage, loss of one or more transformers at a substation, or utility supply problems. Rated vehicle power and performance is not available, but reduced operation is possible assuming that on-board logic will automatically degrade the performance of auxiliaries. The Emergency Minimum Operating Voltage Limit is 70% of the Nominal Operating Voltage. As per AREMA recommendation, this limit applies to vehicle design only and is not used as criteria for a system design.

The traction power supply system voltages were used as an input to the computer simulations and the calculated distribution system voltages were used as criteria to evaluate the simulated system performance. For computer runs simulating all systems in service, *i. e.*, all substations and feeders in service, the lowest train voltage along the line should not fall below the Normal Lower Voltage Limit. For computer runs simulating system outages, *i. e.*, substation or transformer/rectifier out-of-service, the lowest train voltage along the line should not fall below the Emergency Minimum Operating Voltage.

Considering the AREMA recommendations, the traction power supply and distribution system voltage levels were developed for this study as shown in Table B-1.

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[15] **AREMA Manual for Railway Engineering**, Chapter 33, Part 3.

Table B-1 - Voltage Criteria

Traction Power System		Electrification System Voltage (V)		
		1,500 V DC	12.5 kV AC	25 kV AC
Supply System	Normal Upper Voltage Limit	1,600	13,750	27,500
	Nominal Operating Voltage Limit	1,500	12,500	25,000
Distribution System	Normal Lower Voltage Limit	1,200	10,000	20,000
	Emergency Minimum Operating Voltage	1,050	8,750	17,500

Investigations regarding the possible conversion of the existing 1,500 V DC voltage to 12.5 kV AC or 25 kV AC electrification voltage will be part of Task 3.

B.2 LOAD CURRENTS

Approximate current carrying capacity of the Metra distribution system is estimated in Table B-2 and B-3.

Table B-2 - Catenary Conductor Ampacity - Mainline North of 63rd Street, South Chicago Branch, and Blue Island Branch

Conductor	Number of Conductors	Size	Material	Approximate Ampacity (A)
Messenger Wire	1	$^{13}/_{16}$", 7-CW Wires, 12 Cu Wires	Copperweld-Copper	610
Auxiliary Messenger Wire	1	4/0 AWG	Hard Drawn Copper	480
Contact Wire	2	4/0 AWG	Hard Drawn Copper	780
			Total Ampacity	**1,870**

Table B-3 - Catenary Conductor Ampacity - Mainline South of 63rd Street

Conductor	Number of Conductors	Size	Material	Approximate Ampacity
Messenger Wire	1	$^{13}/_{16}$", 7-CW Wires, 12 Cu Wires	Copperweld-Copper	610
Auxiliary Messenger Wire	1	1/0 AWG	Hard Drawn Copper	310
Contact Wire	2	4/0 AWG	Hard Drawn Copper	780
			Total Ampacity	**1,700**

The ampacity values of conductors are obtained using the procedure and the table published in the AREMA Manual for Railway Engineering, Chapter 33, Electrical Energy Utilization, Part 4. The ampacities are calculated based on the following conditions:

- Ambient air temperature: 100°F, (37.8°C) along the open route
- Conductor operating temperature: 167°F, (75°C)
- Emissivity: 0.5
- Wind velocity: 2 ft/sec, (0.61 m/s)
- Contact wire wear: 30% (70% of the conductor original cross-section area remains).

In order to prevent overheating and annealing of catenary system conductors, the conductor RMS currents predicted by the study should be below the conductor ampacities.

B.3 SUBSTATION POWER DEMANDS

In accordance with the Extra Heavy Duty load cycle, the substation transformer/rectifier units are rated to enable the substations to supply the continuous load and overloads. Continuous rating is defined as the capability to supply rated power indefinitely. After constant temperature of all equipment at a substation is reached following operation at 100% rated power, the substations should be capable of supplying the following overload cycle:

- Two hours at 150% of rated load with five evenly spaced periods of one minute each at 300% of rated load, followed by,
- Fifteen second period at 450% of rated load.

The traction power substation continuous and overload ratings are summarized in Table B-4.

Table B-4 - Continuous and Overload Ratings of Traction Power Substations

Demand Period	Substation Rating (% of Rated Power)
Continuous	100
2 Hours	150
1 Minute, five evenly spaced periods of one minute each	300
15 Seconds	450

The traction power system simulations were performed for the peak demand period, the so called rush hour, and the individual substation maximum average power demands were calculated for the 2-hour, 1-minute, and 15-second time intervals as indicated in Table B-4. In order to assess existing substation adequacy, the calculated power demands should be compared with the individual substation continuous rating and overload ratings at the corresponding time intervals.

Appendix C - TPS INPUT DATA

The TPS input data are shown in the following Tables:

- Alignment Data
  - Gradients, Table C-1
    - Mainline, Table C-1a
    - South Chicago Branch, Table C-1b
    - Blue Island Branch, Table C-1c
  - Speed Restrictions, Table C-2
    - Mainline, Table C-2a
    - South Chicago Branch, Table C-2b
    - Blue Island Branch, Table C-2c
  - Passenger Station Locations, Table C-3
    - Mainline, Table C-3a
    - South Chicago Branch, Table C-3b
    - Blue Island Branch, Table C-3c
- Train Data
  - Electrical Data, Table C-4
  - Mechanical Data, Table C-5
  - Performance Data, Table C-6
  - Propulsion and Braking System Data, Table C-7
    - Tractive Effort vs. Speed Curve Data, Field Weakening Disabled, Figure C-1
    - Tractive Effort vs. Speed Curve Data, Field Weakening Enabled, Figure C-2

C.1 ALIGNMENT DATA

The Metra alignment gradients, speed restriction, and passenger station locations were obtained from Metra Operations Profile, Electric District dated April, 2000. The passenger station location table also shows the train dwell time and load factors. The load factor is a percentage of passengers on board and vehicle passenger capability, and is applicable to rush hour operation. For the purposes of the study, fully loaded trains were assumed, *i.e.*, with load factor of 100%.

Excel Table C-1

Excel Table C-2

Excel Table C-3

C.2 TRAIN DATA

Tables C-4 though C-7 show the Electrical Data, Mechanical Data, Performance Data, and Propulsion and Braking System Data of the Metra self-propelled, gallery type, Highliner cars.

Table C-4 - Electrical Data

Data		MU	Units
Pantograph Voltage	Nominal	1,500	V
	Maximum	1,790	V
	Minimum	1,050	V
Auxiliary Power		35	kW

Table C-5 - Mechanical Data

Data		Leading MU	Trailing MUs	Units
Length		85	85	ft
Frontal Area		115	N/A	ft^2
Number of MUs per Train		1	Varies	
Flange Resistance Coefficient, estimated		0.045	0.045	lbs/ton/mph
Air Drag Resistance Coefficient	Leading MU	0.0024		$lbs/ton/mph^2$
	Trailing MUs		0.00034	$lbs/ton/mph^2$
Weight	Empty	70.0	70.0	tons
	Full Load	82.1	82.1	tons

Table C-6 - Performance Data

Data	MU	Unit
Speed, Maximum Operating	75.0	mph
Acceleration Rate, Normal	1.0	mphps
Braking Rate, Normal	1.0	mphps

Table C-7 - Propulsion and Braking System Data

Data	MU
Tractive Effort vs. Speed Characteristic	Refer to Figure C-1, Field Weakening Disabled
	Refer to Figure C-2, Field Weakening Enabled
Propulsion and Regeneration System Efficiency, Maximum	0.88

Appendix D - TPS RESULTS

The TPS runs are performed for both outbound and inbound runs of each train type. The following TPS results are presented in this Appendix for the Mainline, Randolph Street to University Park route.

- Express Trains, Harvey Zone
  - Field weakening disabled and maximum train speed limit of 65 mph, Table D-1 southbound direction, Table D-2 northbound direction.
  - Field weakening enabled and maximum train speed limit of 65 mph, Table D-3 southbound direction, Table D-4 northbound direction.
  - Field weakening enabled and maximum train speed limit of 75 mph, Table D-5 southbound direction, Table D-6 northbound direction.
- Express Trains, Flossmoor Zone
  - Field weakening disabled and maximum train speed limit of 65 mph, Table D-7 southbound direction, Table D-8 northbound direction.
  - Field weakening enabled and maximum train speed limit of 65 mph, Table D-9 southbound direction, Table D-10 northbound direction.
    - Field weakening enabled and maximum train speed limit of 75 mph, Table D-11 southbound direction, Table D-12 northbound direction.
- Express Trains, University Park Zone
  - Field weakening disabled and maximum train speed limit of 65 mph, Table D-13 southbound direction, Table D-14 northbound direction.
  - Field weakening enabled and maximum train speed limit of 65 mph, Table D-15 southbound direction, Table D-16 northbound direction.
  - Field weakening enabled and maximum train speed limit of 75 mph, Table D-17 southbound direction, Table D-18 northbound direction.

Appendix E - ENS INPUT DATA

Data collected for the ENS computer runs are presented in the following Tables:

- Traction Electrification System Basic Per Unit Data, Table E-1
- Utility System Data, Table E-2
- Substation Data, Table E-3
- Traction Power Distribution and Return System Data, Table E-4
- Distribution System Impedances - Per Unit Values, Table E-5
  - Mainline, Table E-5a
  - South Chicago Branch, Table E-5b
  - Blue Island Branch, Table E-5c

E.1 PER UNIT SYSTEM

The ENS input data are represented in the program in the per-unit system. By expressing system constants and variables in per-unit, comparison of performance of equipment at different ratings is simplified. Per-unit values are defined by the ratio shown in Equation E-1:

$$Per\ Unit\ Value = A\ Number/Base\ Number \quad \text{(E-1)}$$

For electrical variables, the following per-unit values are defined:

- Per-Unit Voltage = Voltage/Base Voltage
- Per-Unit Current = Current/Base Current
- Per-Unit Impedance = Impedance/Base Impedance
- Per-Unit Power = Power/Base Power

The voltage, current, impedance and power must be in the same units as their base values. Any convenient number can be selected as a base. By assigning a base value to any two variables, the bases for the remaining two are automatically fixed in accordance with expressions:

- Voltage = Impedance x Current
- Power = Voltage x Current

For convenience, the Base Voltage and the Base Power are selected and the Base Current = Base Power/Base Voltage and Base Impedance = Base Voltage/Base Current. The selection of the Base Voltage and the Base Power is quite arbitrary and has no relationship to the substation ratings.

In practice, it is often convenient to transfer directly from ohmic impedances to per-unit resistances using Equation E-2:

$$Per\ Unit\ Ohms = (Ohms \times Base\ kVA)/(Base\ kV^2 \times 1{,}000) \quad \text{(E-2)}$$

E.2 SYSTEM RESISTANCES

The electrical utility system and the traction power supply, distribution, and return systems are represented by resistances which are determined from the system and conductor characteristics. The following tables present the resistance and reactance data in the per-unit system for the existing 1,500 V DC power system.

Appendix F - COMMUNICATIONS SYSTEM DESIGN

The following reference drawings are shown in this Appendix:

- Drawing F-1 - SCADA System Interconnection Block Diagram
- Drawing F-2 - Microwave/Fiber Optic OC-3 Network Diagram
- Drawing F-3 - South Electric District Fiber Optic and Copper Cable Network

Appendix G - LIGHT AND POWER TRANSMISSION LINE

The Light and Transmission Line system data are presented in the following Tables:

- Transmission Line Loading, Year 2000, Table G-1
- Estimate of Transmission Line Utilization - Light and Power Circuits, Table G-2
- Estimate of Transmission Line Utilization - Signal Circuits, Table G-3

Table G-1 - Transmission Line Loading, Year 2000

Substation Source	Connected Load (kVA)		
	Mainline	South Chicago Branch	Blue Island Branch
Jackson Blvd.	Not Available	-	-
16th Street	1,300	-	-
Brookdale	1,600	-	-
Cheltenham	-	150	-
2Front Avenue	1,600	-	-
Laflin	-	-	160
Harvey	410	-	-
Vollmer	560	-	-
Matteson	Not Available	-	-
University Park	Not Available	-	-

Appendix H - NEW SUBSTATION COST ESTIMATES

Cost estimates for the Metra Electric District augmentation by four package-type substations are presented in the following Tables:

- Traction Power Supply System Cost Estimate Summary, Mainline, Table H-1
- Mainline Substation Cost, Single Transformer/Rectifier, 8 DC Feeders, Table H-2
- Mainline Substation Cost, Single Transformer/Rectifier, 4 DC Feeders, Table H-3